



Fungal decay resistance, formaldehyde emission and weathering resistance of plywood modified with phenol-formaldehyde resin with partial substitution of phenol by pyrolysis cleavage products of softwood kraft lignin

Johannes Karthäuser¹ · Andreas Treu² · Erik Larnøy² · Holger Militz¹ · Gry Alfredsen²

Received: 21 October 2024 / Accepted: 16 June 2025 / Published online: 19 July 2025
© The Author(s) 2025

Abstract

Wood modification by impregnation with phenol-formaldehyde (PF) resins is a promising method to improve the woods' fungal decay resistance, weathering resistance, and dimensional stability. Recent research indicates that 30% of the non-renewable phenol may be substituted by renewable softwood kraft lignin cleavage products obtained through microwave-assisted pyrolysis. *Pinus sylvestris* sapwood modified with this resin has good fungal decay resistance but slightly enhanced formaldehyde emission. While these results on solid wood indicate a high potential of the method, the properties of modified plywood may differ, and the weathering resistance has not been studied. In this study, formaldehyde emission, weathering resistance and fungal decay resistance against three basidiomycetes (*Trametes versicolor*, *Rhodonia placenta*, and *Gloeophyllum trabeum*) of plywood modified with pure PF resin and PF resin with 30% substitution of the phenol by lignin cleavage products were analysed. The 30% lignin cleavage product substitution didn't affect the plywood's fungal decay resistance, with less than 1% initial mass loss in all modified specimens. While the decay resistance improved significantly for all modified samples compared to reference samples, weathering resistance slightly declined with phenol substitution compared to pure PF resin modification. The formaldehyde emissions of the plywood modified with both resins were in similar ranges to that of unmodified reference plywood. Overall, plywood with good properties for exterior applications may be produced even with the substitution of 30% of the phenol by lignin cleavage products, allowing for increased use of renewable resources.

1 Introduction

Wood and wood-based products such as plywood or laminated veneer lumber (LVL) are increasingly used for exterior applications, e.g., for cladding (Grinins et al. 2021; Bicke 2019). There are many reasons for this, amongst them being the positive environmental impact due to the substitution of non-renewable and energy-intensive building materials

(such as concrete), as well as the high strength-to-weight ratio (Hill 2006). However, using a biological material such as wood also presents different challenges. Wood, especially in exterior applications, is prone to swelling and shrinking, leading to crack formation, discolouration and damage by weathering, as well as decay by fungi or other organisms (Evans 2008).

There are numerous factors affecting the weathering of wood during its service life, including solar radiation, reaction with molecular oxygen, water, heat, wind-blown particulate matter, atmospheric pollutants and specialised microorganisms (Feist 1989). However, the superficial nature of the weathering of wood indicates that irradiation plays the major role (Evans 2008). An exception to this is the formation of surface checks or cracks due to dimensional changes, which can reach depths of several millimetres (Evans et al. 2000).

✉ Johannes Karthäuser
jkarthaeuser@gwdg.de

¹ Department of Wood Biology and Wood Products, Faculty of Forest Sciences and Forest Ecology, University of Goettingen, Buesgenweg 4, D-37077 Goettingen, Germany

² Department of Wood Technology, Norwegian Institute of Bioeconomy Research (NIBIO), P.O. Box 115, NO-1431 Ås, Norway

While celluloses and hemicelluloses absorb light, the main effect of the photodegradation of wood is the degradation of lignin, due to its very effective light absorption (Kataoka et al. 2004). Lignin cleavage products include guaiacoxyl, cetyl, and phenacyl radicals (George et al. 2005). The degradation of lignin (and leaching of coloured lignin cleavage products) is responsible for the discolouration of wood (Evans 2008).

As mentioned above, another major factor in the weathering of wood is the swelling and shrinking due to moisture interaction, which results in the formation of checks and cracks (Feist 1989). The interaction with water also plays a role in weathering because the lignin fragments and hemicellulose-derived sugars from photodegraded wood are leached. Additionally, water may hydrolyse lignin and hemicelluloses. However, measurements of such effects are scarce (Evans 2008).

Another large factor that may influence wood in exterior applications is fungal decay. It can be divided into aesthetic disfigurements, caused by discolouring fungi, and decay, caused by decay fungi. While discolouring fungi can affect the visual appearance and water absorptivity of the wood, decay fungi can alter the wood's strength properties. Decay fungi can be separated into brown-rot fungi, white-rot fungi and soft-rot fungi. Brown-rot fungi depolymerise the hemicellulose and cellulose, leaving behind a brown modified lignin (Wilcox 1978; Winandy and Morrell 1993). White-rot fungi either selectively decompose wood in such a way that a cellulose-enriched material remains, or decompose lignin, hemicelluloses and cellulose simultaneously (Eriksson et al. 1990). Brown-rot and white-rot decay is caused by basidiomycetes, while soft-rot decay is caused by ascomycetes and deuteromycetes (Goodell et al. 2008); this study focuses on the fungal decay by basidiomycetes. Generally, coniferous timber is more susceptible to brown-rot decay, while hardwood is oftentimes degraded by white-rot fungi (Duncan and Lombard 1965; Zabel and Morrell 2020).

A method to reduce both fungal decay and ageing due to weathering, as well as to increase the dimensional stability of the wood, is the modification of the wood with impregnation resins (Stamm and Baechler 1960; Jirouš-Rajković and Miklečić 2021). During impregnation modification, monomeric synthetic resins are deployed into the wood's cell wall in a swollen state and thermally cured therein. This treatment fixates the wood in a swollen state, which reduces swelling and shrinking of the material in service (Stamm and Seborg 1936). Due to the hindered access to the cell wall and hydroxy groups, the fungal decay of the treated materials is effectively reduced (Stamm and Baechler 1960). In contrast to preservatives, wood modification operates with a non-biocidal mode of action, preventing the leaching of biocidal chemicals into the environment (Hill 2006).

For exterior applications, a required property of the chosen impregnation resin is high stability against decomposition by water. One type of impregnation resins that fit this criterium is phenol-formaldehyde (PF) resins. Additionally, the advantages of PF resins include their low cost, excellent mechanical properties, photostabilising properties, and easy synthesis. These properties make PF resins an excellent candidate for exterior applications (Kalami et al. 2017; Fleckenstein et al. 2018; Grinins et al. 2021). However, due to the non-renewable origin of phenol and its high toxicity against humans (before curing), the substitution of phenol in PF resins (not only for the purpose of wood impregnation) has been a research goal (Sarika et al. 2020).

One of the candidates for replacing phenol is lignin, the second most abundant biomass on Earth. Lignin is a polymer that consists of phenylpropanoid units, hence having a similar structure to phenolic resins. This similarity has sparked interest and, especially in the field of adhesives, the substitution of phenol by lignin in phenol-formaldehyde resins has been extensively discussed (Sarika et al. 2020; Huang et al. 2022). For the application as an adhesive, the large molecular size of the lignin macromolecules is suitable and may even be an advantage (Kamke and Lee 2007). However, for wood modification, this would be a disadvantage. This is because, for effective wood modification, the modifying agent should enter the wood's cell wall. For this, it must pass through micropores with a diameter of 2–4 nm in swollen state (Furuno et al. 2004; Hill 2006; Biziks et al. 2019). Hence, for this application, the lignin must be cleaved into smaller molecules.

Studies on the fungal decay resistance of solid wood treated with a PF resin, with a 30% substitution of phenol by microwave-pyrolysis lignin cleavage products (LCP), indicated a high potential of the modification. Even at a low resin concentration of 6.25% solid content, only initial decay was detected for *Trametes versicolor*, *Rhodonia placenta*, and *Gloeophyllum trabeum*. Differences between this modification of solid wood compared to veneer-based composites and the effect of weathering have not been studied (Karthäuser et al. 2024a). Fleckenstein et al. (2018) substituted 40% of the phenol by different lignin cleavage products. LVL produced from veneers with a weight% gain (WPG) of about 40% of the resin had good resistance against decay by *T. versicolor* and *Coniophora puteana*. Artificial weathering, according to EN 927-6, indicated that the treatment reduces discolouration and crack formation of LVL. While these results indicated that the method significantly improves the wood properties, several questions remained. The LCP have not been characterised, and they were added after synthesis of the resin, so that they could not form prepolymers with the formaldehyde (Fleckenstein et al. 2018; Fleckenstein 2018).

The aim of this work was to investigate if the substitution of phenol by LCP, as an impregnation resin for wood modification, can be applied to produce modified plywood for exterior applications. For this, *Pinus sylvestris* veneers were modified with a pure PF resin, as well as a PF resin in which 30% of the phenol was substituted by lignin cleavage products. Five-layered plywood boards with and without modification were produced. The resistance against fungal decay by the brown-rot fungi *G. trabeum* and *R. placenta*, as well as the white-rot fungus *T. versicolor* was analysed. Additionally, the ageing of the plywood was studied using artificial ageing, and the formaldehyde emission was determined.

2 Materials and methods

2.1 Pyrolysis of lignin and synthesis of impregnation resins

The LCP were obtained using low-temperature microwave-assisted pyrolysis, as described in Karthäuser et al. (2023). Commercial softwood kraft lignin (“Lineo™”, Stora Enso Oyj, Helsinki, Finland) was cleaved via vacuum low-temperature microwave-assisted pyrolysis. The main components of the LCP were Guaiacol ($8.1 \pm 0.9\%$), 4-Methylguaiacol ($13.8 \pm 0.8\%$), 4-Ethylguaiacol ($6.8 \pm 0.5\%$), and 4-Prop-1-enylguaiacol ($3.2 \pm 0.0\%$).

The synthesis of the resin was carried out as described in Karthäuser et al. (2023). In short, one PF resin (100 PF) with molar ratios of phenol: formaldehyde: NaOH of 1:1.5:0.1 and one PF resin in which 30% of the phenol were substituted by LCP (70/30 LF) with molar ratios of phenol+LCP: formaldehyde: NaOH of 1:1.38:0.1 were prepared. The phenol (and LCP) and NaOH (50% solution in water) were added to a flask and heated to 55 °C to melt the phenol. Afterwards, the formaldehyde (37% solution in water) was added to start the reaction. The temperature was adjusted to 65 °C for 4 h.

Table 1 WPG, thickness, and density of the plywood measured for the specimens treated with different resins and resin solid contents

Resin	Solid content (%)	Plywood WPG (%)	Thickness plywood (mm)	Density plywood (g/cm ³)
Reference	–	–	13.7±0.2	0.64±0.01
100 PF-L	6.25	6.7±2.1	14.2±0.2	0.67±0.03
100 PF -M	12.50	13.2±3.4	13.8±0.5	0.70±0.01
100 PF-H	18.75	17.9±2.7	13.6±0.4	0.78±0.02
70/30 LF-L	6.25	6.1±2.5	14.1±0.2	0.67±0.02
70/30 LF-M	12.50	14.4±1.8	13.8±0.3	0.68±0.02
70/30 LF-H	18.75	18.9±3.1	13.5±0.0	0.73±0.01

2.2 Plywood production

The plywood was produced and characterised as described in Karthäuser et al. (2024b). In short, untreated, 100 PF treated, and 70/30 LF treated five-layered plywood boards were produced with *Pinus sylvestris* veneers, with a thickness of about 3 mm. The veneers were impregnated with the respective resin with solid contents of either 6.25, 12.50, or 18.75% (for the artificial weathering tests, only plywood impregnated with 12.50% solid content resins was analysed). The impregnation was achieved with a vacuum (80–100 mbar; 20 min) pressure (11 bar; 30 min) treatment. Before hot-pressing, the veneers were carefully oven-dried with a final drying temperature of 80 °C. The plywood was produced using a commercial one-component phenol-formaldehyde adhesive, which was manually brushed onto the veneers with an adhesive consumption of 166.5 ± 33.2 g/m². The plywood was pressed in a LAP 40 hot-press (Gottfried Joos GmbH & Co.KG, Pfalzgrafenweiler, Germany) at a temperature of 140 °C. The plywood was pressed to a thickness of 13–14 mm with a maximum force of 1.5 N/mm² for 15 min. Afterwards, the plywood was cooled down in a pneumatic press to reduce deformation. Finally, the plywood was heated up to 140 °C for 10 h to ensure thorough curing of the impregnation resins. Untreated plywood was produced as a reference using the same procedure.

The plywoods’ WPG, thickness, and density, as described in Karthäuser et al. (2024b), are listed in Table 1.

2.3 Plywood analysis

2.3.1 Fungal decay resistance

Samples for the fungal decay experiment with dimensions of 40×40×15 mm were cut from the plywood plates. The specimen size was the same as used in Reinprecht et al. (2012) and was chosen because the samples fit into Kolle flasks used for EN 113-1 (2020) tests. Twenty-two specimens were prepared per resin treatment. The specimens were dried at 103 °C for 24 h, and initial dry weight was recorded. Then, the specimens were leached according to EN 84 (1997), and dry weight after leaching (103 °C for 24 h) was recorded. The samples were conditioned at 65% RH/20°C until a stable weight was achieved. The fungal decay experiment followed the procedure outlined in the European standard EN 113-2 (2020) but used plywood rather than wood blocks. For each fungus, six specimens of each of the differently modified plywoods were analysed. Additionally, four treated specimens were subjected to the same procedure but without fungal inoculum. This was done to determine if mass changes not related to fungal colonisation and decomposition (typically leaching) occur

(in EN 113-1, these specimens are referred to as ‘check test specimens’). Ten specimens of the unmodified plywood were analysed for each fungus as virulence control. For each of the tests, two specimens with the same treatment were added per Kolle flask. The test fungi were the two brown-rot fungi *Gloeophyllum trabeum* (BAM Ebw. 109) and *Rhodonia placenta* FPRL 280 and the white-rot fungus *Trametes versicolor* (CTB 863 A). The wood samples were removed from the flasks after 16 weeks of incubation, carefully cleaned of any mycelium, and weighed. They were then dried at 103 °C for 24 h, and the final dry weight was recorded. The mass loss (initial dry weight to dry weight after decay) and wood moisture content (after the decay test) were calculated.

2.3.2 Formaldehyde emission

Specimens with dimensions of 150×50×15 mm were cut from the plywood. After the production of specimens, the samples were stored in aluminium foil to avoid formaldehyde emission prior to the measurement. The formaldehyde emission of the plywood samples was determined using two different methods. Firstly, the desiccator method was used according to JIS A 1460 (2021). Briefly, nine plywood samples were placed in a metal frame within a desiccator containing 300 ml water at the bottom. The water absorbed formaldehyde in the desiccator for 24 h. Then, the water sample was mixed with acetylacetone-ammonium acetate solution, to be able to quantify formaldehyde by using absorption spectrophotometry. The absorbance was measured at 412 nm in a 5 cm absorption cell with a Mettler Toledo Excellence UV/VIS Spectrophotometer UV5 (Mettler Toledo, Columbus, OH, USA). The measurement was done according to JIS A 1460 (2021).

Secondly, the leaching water from the EN 84 (1997) procedure was analysed for its formaldehyde content according to the same method as above.

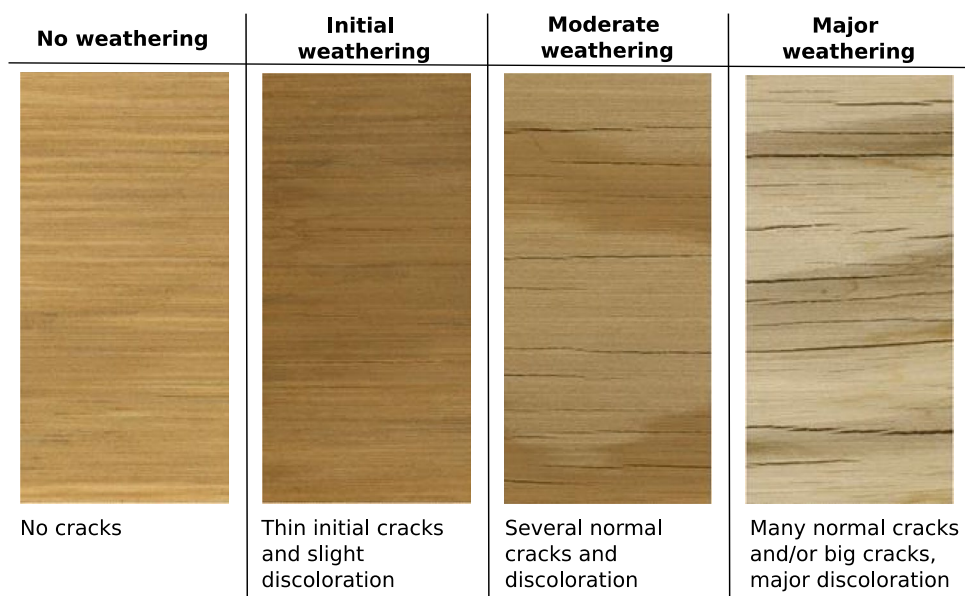
2.3.3 Resistance to surface discolouration and crack formation by weathering

Weathering tests were carried out according to EN 927-6 (2006). For this, six specimens with dimensions of 150×75×15 mm (all cut in such a way that the long side was in the longitudinal direction) were cut from the plywood plates. The specimens were sanded to obtain a clean surface, and pictures of the specimens were produced by scanning with an Expression 11,000 XL scanner (Seiko Epson K.K., Suwa, Japan). The specimens were secured in sample holders with exposure windows of 95×64 mm. Then, the specimens were exposed to 24 h of high relative humidity at 45 °C, followed by 48 cycles of UV exposure (2.5 h, 60 °C, 0.89 W/(m²nm) at 340 nm) and water spraying (0.5 h, 6–7 l/min) in a QUV Accelerated Weathering Tester (Q-Lab Corporation, Cleveland, OH, USA). This exposure was repeated twelve times, and scans of the specimens were taken after each cycle.

Considering that the specimen evaluation in EN 927-6 (2006) is specifically for coating systems, the specimens herein are not evaluated according to the standard. Instead, the results are presented in three ways:

1. The scanned specimens are presented as figures.
2. The specimens are separated into four categories: no weathering, initial weathering, moderate weathering, and major weathering. Examples of the four categories are presented in Fig. 1.

Fig. 1 Examples of the categorisation of the specimens according to surface weathering effects



- To evaluate the specimens' discolouration, the average colour of the exposed surface was determined (supplementary information).

2.3.4 Statistical analysis

For comparison of means, Tukey HSD was performed using JMP®, Version 16, SAS Institute Inc., Cary, NC, USA, 1989–2023. We used a probability of 0.05 as a statistical type-I error level.

3 Results and discussion

3.1 Fungal decay resistance

All the treated plywood performed well with mass loss below 0.5% for all treatments (Fig. 2). The mass loss of control plywood samples was $16.92 \pm 1.25\%$ for *R. placenta*, $8.94 \pm 1.63\%$ for *G. trabeum*, and $10.46 \pm 1.63\%$ for *T. versicolor*.

The reduced mass loss of the treated specimens is in line with solid wood modified with the same treatments (Karthäuser et al. 2024a). The mass loss of the control plywood samples is lower than observed in the literature for solid wood. For example, in Kwaśniewska-Sip et al. (2018), Scots pine sapwood samples with dimensions of $50 \times 25 \times 15$ mm had a mass loss of $24.2 \pm 2.2\%$ against *T. versicolor*, $30.4 \pm 4.0\%$ against *G. trabeum*, and $28.3 \pm 4.9\%$ against *R. placenta*. Similarly, in Karthäuser et al. (2024a), higher mass losses of control specimens after decay were reported. However, due to the small dimensions of the

specimens, direct comparison with the plywood specimens is more difficult.

The lower mass loss of untreated plywood in this study compared to untreated solid wood from earlier studies could be explained by differences between plywood and solid wood and is known from earlier research (Van den Bulcke et al. 2011). There are several material properties that may lead to these observed deviations. One of them is that the mass loss in plywood is calculated in relation to both wood and glue, not just wood. This results in a reduced mass loss because of the addition of a material with high fungal decay resistance. Furthermore, the bond line may act as a barrier both towards moisture and fungi. Additionally, the glue might slightly modify wood in untreated samples, but this effect is likely minimal. Finally, the production of the reference plywood was done as with the treated plywood, with the only difference being the impregnation resin. This was done in order to exclude the influence of the process for direct comparison between the specimens. However, this treatment (heating to 140°C) is a major influence on the plywood compared to untreated solid wood and is likely the main influence on the differences in fungal decay of reference specimens.

In addition to changed material properties, there will always be differences between laboratories and fungal strains, as well as variations between wood specimens, which significantly influence the decay rates. In the current study, the mass loss for untreated plywood was lower than for untreated solid wood (Karthäuser et al. 2024a; Kwaśniewska-Sip et al. 2018) or untreated beech plywood (Reinprecht et al. 2012) described in the literature. However, considering the many influences that could lead

Fig. 2 Percent mass loss of plywood after 16 weeks of exposure to the brown-rot fungi *Rhodonia placenta* and *Gloeophyllum trabeum* and the white-rot fungus *Trametes versicolor* ($n=6$ for treated samples, $n=10$ for control). Treatment is given as type of resin followed by level of solid content (L=6.25, M=12.50, H=18.75)

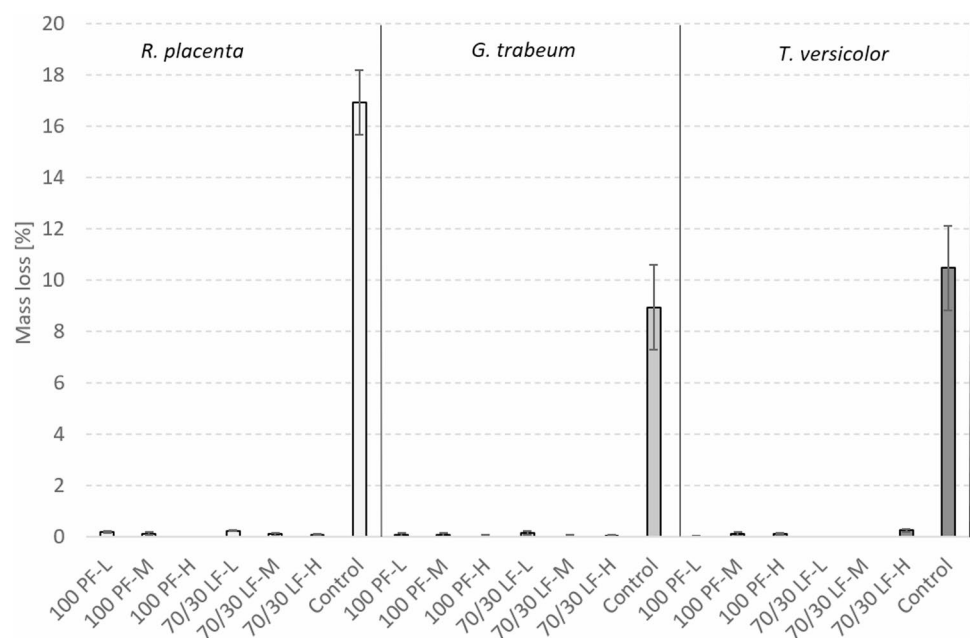
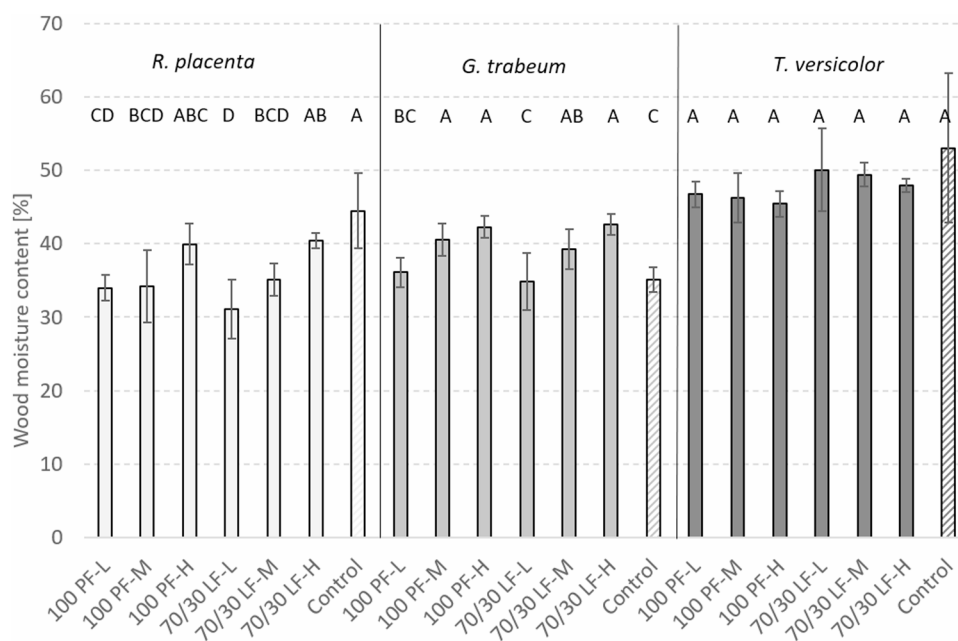


Fig. 3 Moisture content of plywood after 16 weeks of exposure to the brown rot fungi *Rhodonia placenta* and *Gloeophyllum trabeum* and the white rot fungus *Trametes versicolor* ($n=6$ for treated samples, $n=10$ for control). Treatment is given as type of resin followed by level of solid content (L=6.25, M=12.5, H=18.75). Comparison of means of treatments is given, treatments not connected with the same letter are significantly different



to changed fungal decay, the decay rates were within the expected range.

Certain specimens exhibited a slight gain in mass, attributed to the inability to eliminate all fungal mycelia after incubation. As stated by Brischke et al. (2008), mass reduction will only become apparent when the decline in mass resulting from degradation surpasses the increase caused by fungal colonisation. The change in mass for the specimens incubated without fungi (check test specimens) was negligible for all treatments, i.e., less than 0.5%, and indicated that the loss of mass in the specimens exposed to fungi was due to fungal decomposition.

The mean mass loss and moisture content of the specimens can be found in Table S1 in the supplementary information.

For the brown-rot fungi, the wood moisture content after the decay test tended to increase with increasing treatment level for both treatments (Fig. 3). Similar findings were reported for the same treatments and the same fungi for solid wood in Karthäuser et al. (2024a) and by Belt et al. (2023) (with a different treatment). Belt et al. observed that treating Scots pine sapwood with a PF resin reduced the EMC. However, following fungal decay, there was an increase in moisture content as WPG increased. Although the exact cause was not identified, Belt et al. (2023) suggested that this increased moisture uptake could be due to resin presence in the lumen or capillary effects.

The mean wood moisture content of the treated samples exposed to brown-rot fungi was in the range of 31–43%. The wood moisture content after decay was higher for the white-rot fungus *T. versicolor* (45–50%) than for the

Table 2 Formaldehyde content using the desiccator method

Treatment	Formaldehyde (mg/l)	Formaldehyde (mg/kg sample)
Reference	0.095	0.0042
70/30 LF	0.097	0.0042
100 PF	0.083	0.0035

brown rot fungi and there were no significant differences between treatments or compared to control samples. This contradicts the findings for the same treatment and the same fungi for solid wood in Karthäuser et al. (2024a). Solid wood specimens exposed to *R. placenta* had higher wood moisture content in treated samples after 16 weeks of incubation (59–97%) than *G. trabeum* (22–45%) and *T. versicolor* (21–30%). The reason for this could be the different properties of these two materials.

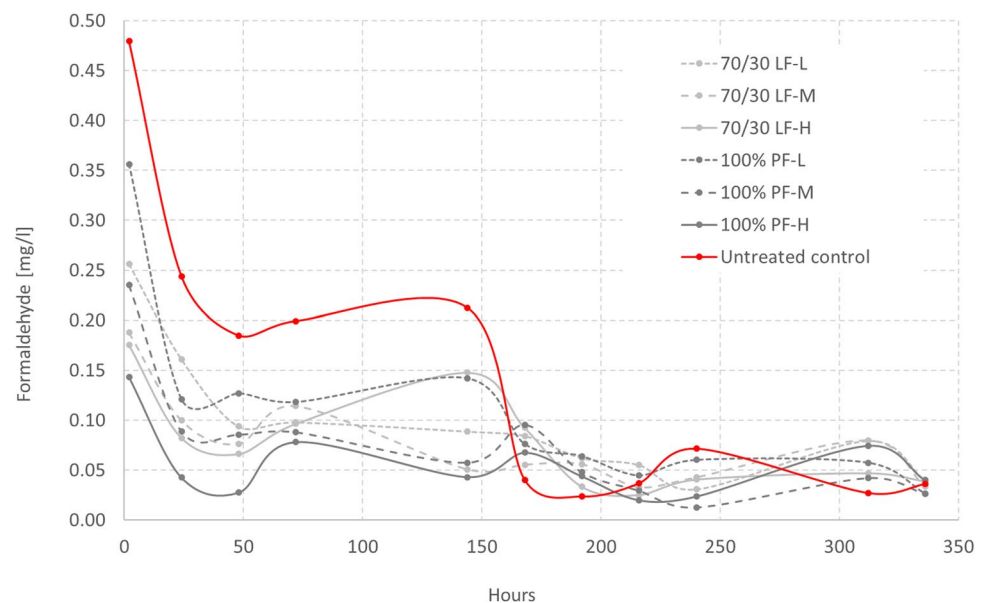
The mean mass loss and moisture content of the check test specimens can be found in Table S1 in the supplementary information.

3.2 Formaldehyde emission

In Table 2, the formaldehyde emissions of the plywood specimens measured with the desiccator method are listed. The formaldehyde emissions were similar to the reference for 70/30 LF and lower than the reference for 100 PF.

As a follow-up, the leaching water from each of the steps in EN 84 (1997) was analysed, including the initial impregnation step (Day 1). The results are visualised in Fig. 4. In accordance with the standard, measurements were omitted during the weekend. Consequently, no

Fig. 4 Results for formaldehyde quantification of the series of leaching water from the EN 84 (1997) leaching procedure. Treatment is given as type of resin followed by level of solid content (L=6.25, M=12.5, H=18.75)



samples were collected between the intervals of 72–144 and 240–312 h in this study.

The formaldehyde analysis confirmed the data from the desiccator method. There was no increase in formaldehyde emissions from the modified samples compared to the untreated control.

In Karthäuser et al. (2024a), the formaldehyde emission of solid pine sapwood modified with similar methods was analysed using leaching water analysis (the second method in this publication). Unlike herein, the formaldehyde emission of the specimens treated with 70/30 LF was increased. There are several factors that could have led to these differences. Firstly, the veneers had a lower WPG than the solid wood described in Karthäuser et al. (2024a), possibly due to a remaining heartwood content in the veneers. Secondly, the curing/production process varies between solid wood and plywood. The plywood is hot-pressed, a process during which large amounts of formaldehyde emission may take place (He et al. 2012). Due to the relatively low temperature of the press during hot-pressing, the authors expect this to play a minor role. However, the different curing programme is expected to influence the formaldehyde emission. Another factor that cannot be neglected is that the specimen itself can have a major influence and that the composite type leads to differences in formaldehyde emission (Böhm et al. 2012).

3.3 Resistance to surface discolouration and crack formation by weathering

The influence of the substitution of phenol by LCP on the weathering of the modified specimens was studied according to EN 927-6 (2006). A comparison of selected

reference, 100 PF treated, and 70/30 LF treated specimens after 0, 6, and 12 QUV cycles is depicted in Fig. 5. Pictures of all specimens are depicted in Fig. S1 to S4 in the supplementary information. The results indicate that both the treatment with 100 PF and with 70/30 LF lead to a reduction of the discolouration and formation of cracks during artificial weathering. After 12 weeks of artificial exposure, the cracks in the surface of the reference samples were significantly larger than those for the modified plywood specimens. Compared to the 100 PF-treated specimens, the specimens modified with 70/30 LF decolourise slightly faster, and a slightly increased formation of cracks was observed.

The decolourisation of specimens was further studied by determining the average colour of the treated specimens' surface, as presented in Table S2 in the supplementary information. The stronger decolouration of untreated specimens was confirmed.

Additional evaluation was carried out by dividing the specimens into four groups: no weathering, initial weathering, moderate weathering, and major weathering. The distributions of evaluations after each QUV cycle are depicted in Fig. 6. After nine cycles, all the reference specimens showed major weathering effects. In contrast, the specimens treated with 100 PF only exhibited moderate weathering effects after 12 cycles, while the specimens treated with 70/30 LF were moderately affected by weathering with the exception of one specimen, which was majorly affected after 10 cycles.

The results presented in Figs. 5 and 6 indicate that the treatment improves the resistance against weathering of the modified wood. A reason for this may be the reduced swelling and shrinking described in Karthäuser et al.

Fig. 5 A comparison of the selected reference, 100 PF-treated, and 70/30 LF-treated specimens after 0, 6, and 12 QUV cycles

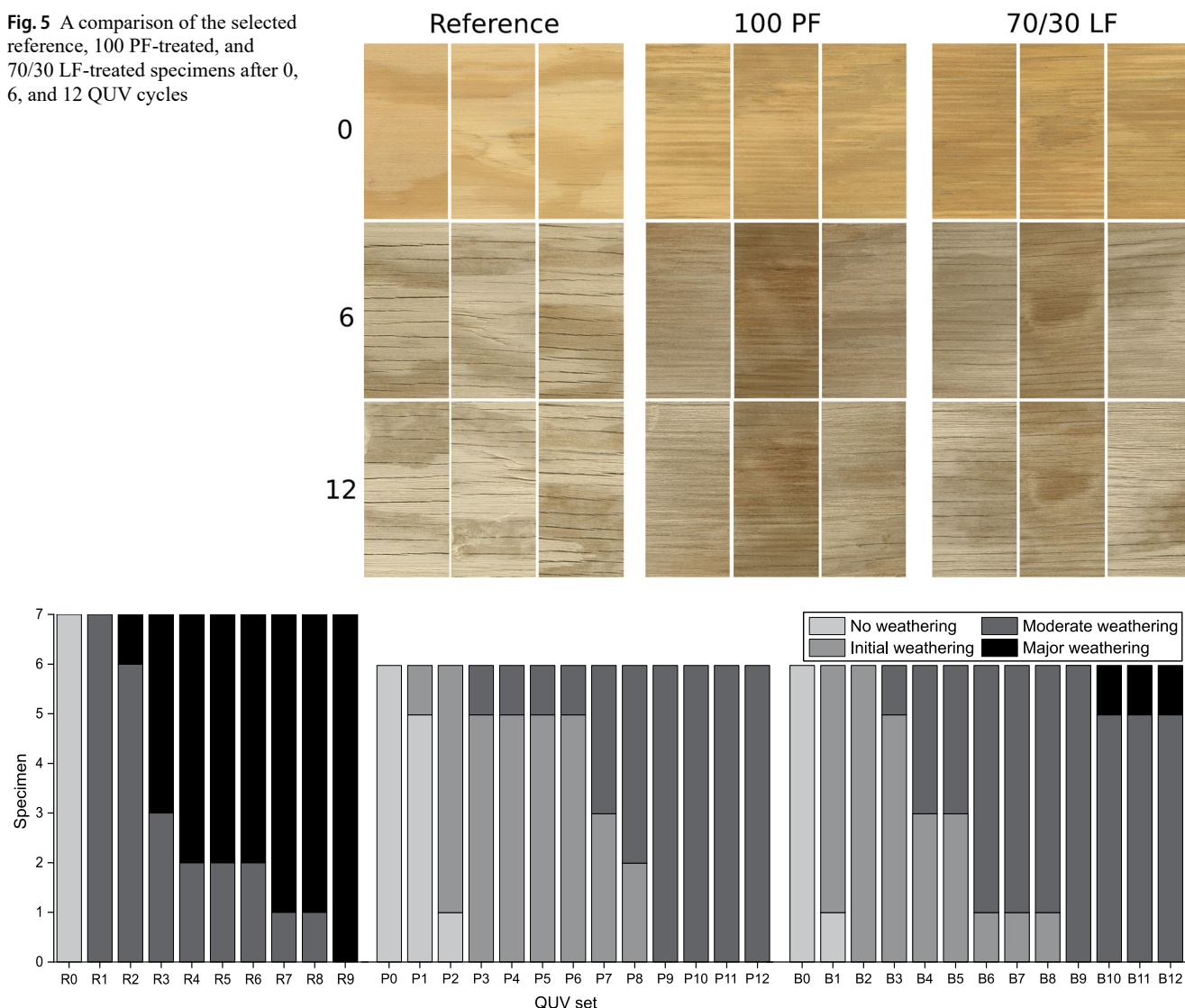


Fig. 6 Weathering evaluation of the reference (R), 100 PF treated (P) and 70/30 LF treated (B) specimens after each cycle of QUV exposure (1–12)

(2024b), which reduces the formation of cracks. One of the main factors of wood alteration due to weathering is the UV degradability of lignin (Evans 2008). The reduced discolouration of the treated specimens may be explained by the addition of a dark resin, which is more stable against discolouration than ligneous structures in wood. Due to the substitution of phenol by LCP, the 70/30 LF resin may contain ligneous structures, which could explain the increased influence of weathering on the specimens compared to the specimens treated with 100 PF resin. To reduce this effect, additives could be used during the synthesis of the resin. However, the increases in crack formation and discolouration are only minor, and the increased protection of the wood by modification with 70/30 LF resin compared to untreated specimens may be

considered efficient, hence making additional measures redundant.

4 Conclusion

This study aimed to assess the impact of partial replacement of phenol in phenol-formaldehyde resins with LCP derived from the pyrolysis of softwood kraft lignin for plywood veneer impregnation. Specifically, it examined how this substitution affects the plywood's fungal decay resistance, formaldehyde emission, and weathering resistance. The fungal decay resistance of the plywood specimens was significantly improved by both the treatment with pure PF resin and the resin with 30% phenol substitution. All treated specimens, even with a low WPG of 10%, had below 1%

mass loss due to fungal decay by white-rot and brown-rot fungi after 16 weeks of exposure.

The formaldehyde emission of both modified plywoods was similar to that of unmodified reference plywood. This was confirmed by two methods: the analysis of leaching water and the desiccator method.

Finally, the weathering resistance of the plywood modified with both resins was significantly higher than that of untreated reference plywood. The substitution of phenol by pyrolysis oil does, however, slightly accelerate the discolouration due to UV degradation and the formation of cracks.

Overall, the substitution of phenol by pyrolysis oil only has a minor effect or no effect on the measured plywood properties. Both modification methods led to plywood with favourable properties compared to untreated plywood. Thus, the substitution of phenol could help to reduce the usage of non-renewable chemicals and, at the same time, provide a new purpose for currently underutilised lignin waste streams.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s00107-025-02294-0>.

Acknowledgements The authors acknowledge Dieter Varel from the University of Göttingen for assistance with the artificial weathering experiments, Maik Slabohm from the University of Göttingen for assistance with the plywood production, and Dr. Lucy Martin from the University of Göttingen for proofreading the manuscript. Further, Sigrun Kolstad and Eva Grodås from NIBIO are acknowledged for assistance with the fungal decay experiment and formaldehyde analysis.

Author contributions Method development and conduction of experiments, all authors; Data curation, A.T., G.A., and J.K.; Writing—original draft preparation, J.K.; Supervision, H.M.; writing—review and editing, all authors. All authors have read and agreed to the published version of the manuscript.

Funding Open Access funding enabled and organized by Projekt DEAL. The authors acknowledge support from the Federal Ministry of Education and Research (Germany) and its project promoter Forschungszentrum Jülich GmbH (funding number: 031B0952), as well as the Research Council of Norway (RCN Project no. 305120). The publishing of this article was supported by the Open Access Publication Funds of the Georg-August University of Göttingen.

Data availability The data presented in this study are available upon request from the corresponding author.

Declarations

Competing interests The authors declare no competing interests.

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/>.

References

- Belt T, Suvi K, Kolpinen AT (2023) Relationship between decay resistance and moisture properties in wood modified with phenol formaldehyde and sorbitol-citric acid. *J Mater Sci* 58:13678–13690. <https://doi.org/10.1007/s10853-023-08874-w>
- Bicke S (2019) Dimensionsstabile und pilzresistente Furnierwerkstoffe durch Zellwandmodifizierung mit niedermolekularem Phenol-Formaldehyd [Dimensionally stable and fungal-resistant veneer compounds by cell wall modification with low molecular phenol-formaldehyde]. Dissertation, Georg-August-Universität Göttingen
- Biziks V, Bicke S, Militz H (2019) Penetration depth of phenol-formaldehyde (PF) resin into Beech wood studied by light microscopy. *Wood Sci Technol* 53(1):165–176. <https://doi.org/10.1007/s00226-018-1058-2>
- Böhm M, Salem MZM, Srba J (2012) Formaldehyde emission monitoring from a variety of solid wood, plywood, blockboard and flooring products manufactured for Building and furnishing materials. *J Hazard Mat* 221–222:68–79. <https://doi.org/10.1016/j.jhazmat.2012.04.013>
- Brischke C, Welzbacher CR, Huckfeldt T (2008) Influence of fungal decay by different basidiomycetes on the structural integrity of Norway Spruce wood. *Holz Roh Werkst* 66:433–438. <https://doi.org/10.1007/s00107-008-0257-1>
- Duncan CG, Lombard FF (1965) Fungi associated with principal decays in wood products in the united States. Dept. of Agriculture, Washington
- Eriksson K-EL, Blanchette RA, Ander P (1990) Microbial and enzymatic degradation of wood and wood components. Springer Berlin Heidelberg, Berlin, Heidelberg
- European Committee for Standardization (2020) EN 113-2. (2020). Durability of wood and wood-based products. Test method against wood destroying basidiomycetes. Assessment of inherent or enhanced durability. Brussels, Belgium
- European Committee for Standardization (2020) EN 113-1. (2020). Durability of wood and wood-based products. Test method against wood destroying basidiomycetes. Part 1: Assessment of biocidal efficacy of wood preservatives. Brussels, Belgium
- European Committee for Standardization (2006) EN 927-6:2006 Paints and varnishes - Coating materials and coating systems for exterior wood - Part 6: Exposure of wood coatings to artificial weathering using fluorescent UV lamps and water; German version. Brussels, Belgium
- European Committee for Standardization (1997) EN 84:1997 durability of wood and wood-based products - Accelerated ageing of treated wood prior to biological testing - Leaching procedure. Brussels, Belgium
- Evans PD (2008) Weathering and photoprotection of wood. In: Schultz TP, Militz H, Freeman MH, Goodell B, Nicholas DD (eds) Development of commercial wood preservatives: efficacy, environmental, and health issues. American Chemical Society, Washington, DC
- Evans PD, Wingate-Hill R, Barry SC (2000) The effect of different kerfing and center-boring treatments on the checking of ACQ treated pine posts exposed to the weather. *For Prod J* 50(2):59–64

- Feist WC (1989) Outdoor wood weathering and protection. In: Rowell RM, Barbour RJ (eds) *Archaeological wood: properties, chemistry, and preservation*. American Chemical Society, Washington, DC
- Fleckenstein M (2018) Technische Lignine als biobasiertes Ausgangsmaterial zur Substitution von erdölbasiertem Phenol in Phenol-Formaldehyd-Harzen [Technical lignins as a bio-based starting material for the substitution of oil-based phenol in phenol-formaldehyde resins]. Dissertation, University of Göttingen
- Fleckenstein M, Biziks V, Mai C, Militz H (2018) Modification of Beech veneers with lignin phenol formaldehyde resins in the production of laminated veneer lumber (LVL). *Eur J Wood Prod* 76(3):843–851. <https://doi.org/10.1007/s00107-017-1275-7>
- Furuno T, Imamura Y, Kajita H (2004) The modification of wood by treatment with low molecular weight phenol-formaldehyde resin: a properties enhancement with neutralized phenolic-resin and resin penetration into wood cell walls. *Wood Sci Technol* 37:349–361
- George B, Suttie E, Merlin A, Deglise X (2005) Photodegradation and photostabilisation of wood—the state of the Art. *Polym Degrad Stab* 88(2):268–274. <https://doi.org/10.1016/j.polymdegradstab.2004.10.018>
- Goodell B, Qian Y, Jellison J (2008) Fungal decay of wood: soft-rot-brown-rot-white-rot. Chapter 2. In: Schultz TP, Militz H, Freeman MH, Goodell B, Nicholas DD (eds) *Development of Commercial Wood Preservatives: Efficacy, Environmental, and Health Issues*. ACS Symposium Series 982:9–31, Washington, DC. <https://doi.org/10.1021/bk-2008-0982.ch002>
- Grinins J, Biziks V, Marais BN, Rizikovs J, Militz H (2021) Weathering stability and durability of Birch plywood modified with different molecular weight Phenol-Formaldehyde oligomers. *Polymers* 13(2):175. <https://doi.org/10.3390/polym13020175>
- He Z, Zhang Y, Wei W (2012) Formaldehyde and VOC emissions at different manufacturing stages of wood-based panels. *Build Environ* 47:197–204. <https://doi.org/10.1016/j.buildenv.2011.07.023>
- Hill CAS (2006) *Wood modification: chemical, thermal and other processes*. Wiley, Chichester, England; Hoboken, NJ
- Huang C, Peng Z, Li J, Li X, Jiang X, Dong Y (2022) Unlocking the role of lignin for Preparing the lignin-based wood adhesive: A review. *Ind Crops Prod* 187:115388. <https://doi.org/10.1016/j.indcrop.2022.115388>
- Japanese Standards Association (2021) JIS, A. 1460 (2021). Determination of the emission of formaldehyde from building boards - desiccator method. Tokyo, Japan
- Jirouš-Rajković V, Miklečić J (2021) Enhancing weathering resistance of Wood—A review. *Polymers* 13(12):1980. <https://doi.org/10.3390/polym13121980>
- Kalami S, Arefmanesh M, Master E, Nejad M (2017) Replacing 100% of phenol in phenolic adhesive formulations with lignin. *J Appl Polym Sci* 134(30):45124. <https://doi.org/10.1002/app.45124>
- Kamke FA, Lee JN (2007) Adhesive penetration in wood—a review. *Wood Fiber Sci* 39(2):205–220
- Karthäuser J, Biziks V, Frauendorf H, Hoffmann L, Raskop S, Roggatz D, Militz H (2023) Substituting phenol in phenol-formaldehyde resins for wood modification by phenolic cleavage products from vacuum low-temperature microwave-assisted pyrolysis of softwood kraft lignin. *Cellulose* 30(11):7277–7293. <https://doi.org/10.1007/s10570-023-05295-5>
- Karthäuser J, Treu A, Larnøy E, Militz H, Alfredsen G (2024a) Resistance against fungal decay of Scots pine sapwood modified with phenol-formaldehyde resins with substitution of phenol by lignin pyrolysis products. *Holzforschung* 78(4):231–243. <https://doi.org/10.1515/hf-2023-0119>
- Karthäuser J, Raskop S, Slabohm M, Militz H (2024b) Modification of plywood with phenol-formaldehyde resin: substitution of phenol by pyrolysis cleavage products of softwood kraft lignin. *Eur J Wood Prod* 82(2):309–319. <https://doi.org/10.1007/s00107-023-02029-z>
- Kataoka Y, Kiguchi M, Evans PD (2004) Photodegradation depth profile and penetration of light in Japanese Cedar earlywood (*Cryptomeria Japonica* D. Don) exposed to artificial solar radiation. *Surf Coat Int B: Coat Trans* 87(3):187–193. <https://doi.org/10.1007/BF02699634>
- Kwaśniewska-Sip P, Cofta G, Nowak PB (2018) Resistance of fungal growth on Scots pine treated with caffeine. *Int Biodeterior Biodegrad* 132:178–184. <https://doi.org/10.1016/j.ibiod.2018.03.007>
- Reinprecht L, Kmeot'vá L, Iždinský J (2012) Fungal decay and bending properties of Beech plywood overlaid with tropical veneers. *J Trop for Sci* 24(4):490–497
- Sarika PR, Nancarrow P, Khansaheb A, Ibrahim T (2020) Bio-Based alternatives to phenol and formaldehyde for the production of resins. *Polymers* 12:2237. <https://doi.org/10.3390/polym12102237>
- Stamm AJ, Baechler RH (1960) Decay resistance and dimensional stability of five modified woods. *Prod J* 10(1):22–26
- Stamm AJ, Seborg RM (1936) Minimizing wood shrinkage and swelling. *Ind Eng Chem* 28(10):1164–1169. <https://doi.org/10.1021/i-e50322a009>
- Van den Bulcke J, De Windt I, Defoirdt N, De Smet J, Van Acker J (2011) Moisture dynamics and fungal susceptibility of plywood. *Int Biodeterior Biodegrad* 65(5):708–716. <https://doi.org/10.1016/j.ibiod.2010.12.015>
- Wilcox WW (1978) Review of literature on the effects of early stages of decay on wood strength. *Wood Fiber Sci* 9(4):252–257
- Winandy JE, Morrell JJ (1993) Relationship between incipient decay, strength, and chemical composition of Douglas-fir Heartwood. *Wood Fiber Sci* 25(3):278–288
- Zabel RA, Morrell JJ (2020) *Wood microbiology: decay and its prevention*, Second edition. Academic Press, Amsterdam

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