



Enhancing the durability of pine species: studying the efficacy of copper- and silicone-based liquids as a function of chemical loadings and wood species

Tarcila Rosa da Silva Lins^{1,2} · Lukas Emmerich^{2,3} · Pedro Henrique Gonzalez de Cademartori¹ · Ricardo Lima de Souza⁴ · Ricardo Jorge Klitzke¹ · Márcio Pereira da Rocha¹ · Holger Militz²

Received: 12 December 2025 / Accepted: 11 February 2026 / Published online: 1 April 2026
© The Author(s) 2026

Abstract

Fungal decay significantly affects the performance of wood used for outdoor applications. Both biocidal and non-biocidal treatments have been explored to enhance the resistance of wooden materials against decay fungi. This study evaluated the effects of different concentrations of copper-based and silicone-based products on the durability of different pine species (*Pinus sp.*) against brown-rot fungi. Treated specimens of *Pinus radiata*, *Pinus sylvestris* and *Pinus palustris* were exposed to monocultures of *Coniophora puteana*, *Rhodonia placenta* and *Antrodia vaillantii* after an accelerated ageing procedure. Durability was assessed based on mass loss and durability classes assigned to untreated as well as treated specimens. Both treatments significantly increased the decay resistance, whereas no significant differences could be measured between the wood species or decay fungi. Silicone oil showed a clear concentration–durability relationship: treatments at $\geq 5\%$ provided the maximum protection level and were classified as “very durable” (DC 1) in most cases. For treatments with copper-based preservatives, the highest concentration generally resulted in the highest durability class, although some samples were only moderately durable. This indicated that starting from a concentration of 3%, copper-based treatments contributed to reduce the mass loss. Principal component analysis was applied to verify the relationship between the variables. The results confirmed these patterns and highlighted the potential of intermediate concentrations to optimize the biological durability. Overall, the findings demonstrated that both copper-based and silicone-based treatments effectively enhanced the resistance of sapwood sections of various pine species to different brown-rot fungi, primarily by maintaining low moisture content (MC) and minimizing fungal activity and decay measured on the basis of mass losses (ML) even after fungal exposure.

1 Introduction

Fungal biodeterioration, particularly caused by decay fungi, poses a major threat to the longevity of wood in outdoor applications (Mangini et al. 2025). Pine sapwood shows a much lower resistance to decay processes by wood-destroying fungi than its heartwood which can be attributed to its chemical composition and anatomical characteristics. Whereas a high permeability and hygroscopicity, especially of pine sapwood sections provides advantages for impregnations with liquids which aim at an increased durability, the same characteristic does on opposite promote an increased moisture uptake, which may lead to favourable conditions for fungal colonization inside the wooden structure. Consequently, untreated pine sapwood is generally classified as a material with low resistance to fungal decay, thus a

✉ Tarcila Rosa da Silva Lins
tarcila.lins@hotmail.com

¹ Department of Forestry Engineering and Technology, Federal University of Paraná, Av. Prefeito Lothário Meissner, 623-Jardim Botânico, Curitiba 80210-170, Brazil

² Wood Biology and Wood Products, Faculty of Forest Sciences, University of Goettingen, Buesgenweg 4, D-37077 Goettingen, Germany

³ Wald und Holz NRW, Centre of Forests and Wood-based Industries, Team Wood-based Industries, Carlsaustr. 91A, D-59939 Olsberg, Germany

⁴ Institut Valencià d'Investigacions Agràries (IVIA), Km. 10, CV-315, 7, 46113 Montcada, Valencia, Spain

durability class (DC) 5 ‘not durable’ is assigned according to EN 350 (2020). The latter makes an effective modification or preservation of pine sapwood essential for the case that outdoor applications are aspired.

To mitigate this problem, numerous products and techniques have been developed to enhance wood durability. Biocidal agents, such as copper-based preservatives, act primarily through their toxicity, directly inhibiting fungal proliferation. In contrast, non-biocidal treatments, based on chemical, physical or thermal modifications of the wood ultrastructure (e.g., acetylation, furfurylation, and application of Si-based systems) reduce wood–water interactions, block pores, and increase dimensional stability, thereby decreasing substrate biodegradability (Gérardin 2016; Sandberg et al. 2022).

Although treatment with biocidal formulations remains a common practice for outdoor applications, many contain hazardous substances such as chromated copper arsenate (CCA). The use of CCA has been drastically reduced worldwide due to environmental and health concerns. Indeed, it is now banned in several European countries (Schultz et al. 2007). In Brazil, CCA has been widely applied since the 1970s due to its proven effectiveness, yet it is considered to be Class I – Hazardous according to the Brazilian Association of Technical Standards (Ribeiro et al. 2025). Despite this classification, there are no legal restrictions on its use, raising concerns about leaching or improper disposal, thereby causing soil and water contamination and toxicity to living organisms. Alternatively, chromium- and arsenic-free preservatives containing copper and organic co-biocides (e.g., Cu-HDO) that form insoluble compounds within the wood structure (Kängsepp et al. 2011) have shown high efficacy against decay fungi (Baysal et al. 2017).

In recent decades, research and technological development have increasingly focused on wood modification techniques employing non-biocidal compounds, which provide in-service protection through nontoxic mechanisms (Gérardin 2016; Sandberg et al. 2022). These approaches improve wood performance without relying on toxicity, and their adoption is expected to expand in the coming years, achieving large-scale application for wood protection (Gérardin 2016). Among these, silicone-based formulations have been tested to verify their effectiveness in improving wood properties, such as durability against fungal decay (Mai and Militz 2004).

Numerous studies have demonstrated that both chemical modification and preservative treatments can substantially improve the biological durability of wood (Emmerich et al. 2021a; Kurkowiak et al. 2021; Brischke et al. 2024). These improvements are widely attributed to increased dimensional stability, which makes the material less susceptible to failure originating from swelling and shrinking

processes (Sandberg et al. 2022). This effect of reduced moisture uptake contributes to improved decay resistance, since moisture dynamics, specifically the moisture susceptibility of wood, play a key role in decaying and infestation processes.

After chemical modification or preservative treatment, several factors help to increase durability against biodeterioration, particularly those related to changes in the wood’s chemical composition and structure. These treatments can alter the substrate by depositing substances within macrovoids and cell walls, and by affecting related properties such as moisture dynamics (Treu et al. 2011; Emmerich et al. 2021b). Assessing these factors through adequate quality control is essential to ensure optimal performance of the treated material, since the chemical retention inside the wooden structure, specifically after ageing, is the key parameter related to effective protection. Moreover, determining the minimum effective concentration able to improve biological durability is necessary to ensure cost-effective and scalable industrial application, especially for products containing leachable components.

The aim of the present study was to evaluate the effectiveness of a copper-based biocidal preservative and a non-biocidal silicone-based formulation to enhance biological durability of pine sapwood, with special focus on brown-rot fungi. For this purpose, different pine species were tested in order to validate the general applicability of the treatments of choice along treatable wooden materials with varying densities and origin. Additionally, treatment levels needed to achieve certain protection levels in pine sapwood sections, expressed by durability classes, were studied.

2 Materials and methods

2.1 Wood material and treatment process

2.1.1 Material preparation

Sapwood of longleaf pine (*Pinus palustris* L.), Monterey pine (*Pinus radiata* D. Don) and Scots pine (*Pinus sylvestris* L.) with an average density of 0.56 g cm^{-3} (± 0.04), 0.48 g cm^{-3} (± 0.03) and 0.48 g cm^{-3} (± 0.03), respectively, obtained from forests being located in Brazil, New Zealand and Lower Saxony (Germany), were used for the present study. All specimens selected were free from defects such as cracks, knots, resin pockets, discoloration or decay. Before conducting the treatments, specimens measuring $25 \text{ mm} \times 15 \text{ mm} \times 50 \text{ mm}$ (radial $\times$ tangential $\times$ longitudinal) underwent an oven drying at $103 \pm 2 \text{ }^{\circ}\text{C}$ until constant mass.

Copper-based formulations were used as representatives of biocidal treatments, while silicone oil served as

a representative of non-biocidal treatments. The concentrations were determined based on previous experiments conducted by the research group. The test specimens were impregnated with these formulations at different concentrations, prepared by diluting the products in cold tap water (mass/mass ratio) according to the concentration levels described in Table 1.

2.1.2 Chemical treatment

Kiln-dried specimens were impregnated in a semi-industrial scale impregnation plant at the University of Göttingen by applying a vacuum (5 kPa) for one hour, followed by an overpressure step at 1,200 kPa for two hours. Immediately after treatment, specimens treated with copper-based preservatives were weighed to calculate the chemical uptake, according to Eq. 1.

$$U = \frac{BU}{V} \quad (1)$$

Where: U=Chemical uptake (kg/m³); BU=Biocide uptake (kg); V=specimen volume (m³).

Afterward, impregnated specimens were stored to air dry for two weeks, then dried in an oven at 50 °C for 48 h. Finally, the dry mass and dimensions of the samples treated with silicone oil were measured to calculate the weight percent gain (WPG%) and cell wall bulking (CWB) according to Eqs. 2 and 3 (Emmerich et al. 2020).

$$WPG = \frac{(m_{final} - m_{initial})}{m_{initial}} 100 \quad (2)$$

$$CWB = \frac{(A_{final} - A_{initial})}{A_{initial}} 100 \quad (3)$$

Where: WPG=weight percent gain after impregnation and oven drying at 50 °C (%); m₀=oven-dry mass of untreated wood (g); m_{final}=dry mass after treatment (g); CWB=cell wall bulking after impregnation and drying (%); A_{initial}=initial dry cross-sectional area (radial × tangential) of

untreated wood (mm²); A_{final}=cross-sectional area (radial × tangential) after treatment (mm²).

2.2 Leaching test

Untreated European beech (*Fagus sylvatica* L.) specimens with dimensions of 25 × 15 × 50 mm³ (radial × tangential × longitudinal) were included as virulence controls, and from here on were included in all stages of the experiment. All specimens were subjected to a cold-water leaching according to EN 84 (2020).

After leaching, the specimens were dried at ambient conditions and then kiln-dried at 103 °C until constant mass. Once again, the dry mass and dimensions were measured, and WPG and CWB after leaching were calculated according to Eqs. 2 and 3. Then, the specimens were kept in the climatic chamber (20 °C, 65% RH) until being use for the fungal exposure. Weight loss due to leaching (WLL) was calculated according to Eq. 4.

$$WLL = \frac{(m_{AT} - m_{AL})}{m_{AT}} 100 \quad (4)$$

Where: WLL=weight loss of untreated or treated wood due to leaching (%); m_{AT}=initial dry mass of untreated and treated wood (g); m_{AL}=the mass at 103 °C of untreated and treated wood samples after the leaching process (g).

2.3 Durability assessment

Decay tests with basidiomycete monocultures used three species of brown rot fungi: *Coniophora puteana* (Schum.:Fr) Karst, *Rhodonia placenta* (Fr.) Niemelä, K.H. Larss. & Schigel and *Antrodia vaillantii* (DC.:Fr.) Ryv. The testing procedure followed EN 113-2 (2021). First, conditioned specimens were steam sterilized at 121 °C for 20 min. After sterilization, two specimens of each treatment were placed in a Kolle flask containing the mycelium of the cultivated fungus and positioned on a steel ring to avoid direct contact. Each treatment × species combination was tested with ten replicates (n=10), with two specimens in each vessel,

Table 1 Technical information from manufactures of products used for the wood chemical treatment process

Chemical nature	Copper-based preservative	Silicone oil
	Concentrate based on copper salts (copper carbonate/hydroxide), copper HDO (copper diazonium dioxygen) and boric acid.	Special compounded polysiloxane hydrophilic silicone
Physical form	Concentrated liquid; completely soluble in water	Microemulsion, dilutable with cold water in all proportions.
Density (20 °C)	Approx 1.2 g/cm ³	Approx 0.99 g cm ⁻³
pH	9.6	4.5–5.5
Solid content product	19.8%	18.5%
Concentrations of impregnation formulations	0.75%, 1.5% and 3.0%	1%, 2.5%, 5%, 7.5%, and 10%

corresponding to five culture vessels per combination. After insertion of the specimens, the culture vessels were stored in a chamber with controlled temperature and humidity conditions for 16 weeks.

After the exposure, the specimens were removed from the culture vessels and cleaned to remove any traces of mycelium and immediately weighed. Subsequently, specimens were placed in a drying oven at 103 ± 2.0 °C until constant mass. Finally, the mass loss (ML) and moisture content (MC) of the materials were determined according to Eqs. 5 and 6.

$$ML = \frac{(m_0 - m_{i,0})}{m_0} 100 \quad (5)$$

$$MC = \frac{(m_i - m_0)}{m_0} 100 \quad (6)$$

Where: ML=mass loss after decay testing (%); MC=moisture content after three months incubation (%); m_0 =initial oven-dry mass before incubation (g); m_i =mass after incubation (g); $m_{i,0}$ = oven-dry mass after incubation (g).

Arithmetic means and standard deviations of the calculated mass loss values were obtained per treatment combination. Based on the average of ML values of the test specimens, durability classes were assigned according to EN 350 (2016), as shown in Table 2.

2.4 Statistical analysis

Pearson correlation and principal component analysis (PCA) were carried out using the RStudio software (version 2024.12.0+467), with the aid of the packages *factoextra* for extracting individual coordinates and explained variance, and *ggplot2* for constructing graphs, applying confidence ellipses, and customizing shapes, colors, and themes. PCA was applied to reduce the dimensionality of the dataset by transforming correlated variables into a smaller set of uncorrelated principal components (PCs). The variables included in the PCA were weight percent gain (WPG) and cell wall bulking (CWB) before and after leaching for silicone treated samples; preservative uptake for the preservative-treated samples and mass loss (ML), moisture content (MC), and

durability class (DC) for both treatments. Pearson correlation analyses were conducted for variables previously mentioned, and the two principal components (PC1 and PC2) that explained the greatest proportion of total variance were selected. A scatter plot was constructed using PC1 and PC2 as the axes to visualize sample groupings and trends.

3 Results and discussion

3.1 Mass loss by fungal decay

As can be seen in Fig. 1, both treatments had a concentration-dependent pattern, since as uptake and weight percent gain increased, mass loss decreased. Untreated pine sapwood specimens, in contrast, were classified as slightly durable to non-durable (DC 4–5), a result consistent with the literature (Brischke and Alfredsen 2022), therefore confirming the protection efficacy of the products application.

Although the copper-based preservative had a greater variability among evaluated species (Fig. 1a, c, e), it was observed that mass loss decreased with increasing product concentration, with 3% achieving the lowest values. This correlation of concentration, uptake, and performance reflects the fact that copper is a highly leachable component, whose fixation in wood depends on the concentration of the active ingredient (Humar et al. 2007). Reduced leaching at higher concentrations resulted in greater preservative fixation and increased durability, corroborating the results reported by Treu et al. (2011), Kängsepp et al. (2011), and Temiz et al. (2014).

The increase in wood durability with higher concentrations of copper-based preservative can be attributed to the dose-dependent availability of Cu^{2+} ions, which interfere with the wood degradation mechanisms of brown rot fungi (Civardi et al. 2015). Those authors also explained that in these fungi, copper disrupts key biochemical pathways involved in lignocellulose decomposition, such as free hydroxyl radical generation via Fenton reaction and the associated production of oxalic acid, which regulates pH and metal availability during decay. The inhibition of these oxidative and enzymatic processes reduces the fungi's ability to depolymerize cell wall components, ultimately limiting wood deterioration. Higher preservative concentrations also enhance copper fixation within the wood, creating a reservoir effect that maintains long-term protection and contributes to the improved biological durability observed in this study.

The response to copper treatment is further influenced by the physiological characteristics of the fungal species and the surrounding chemical environment. The three fungal species tested belong to copper-tolerant genera (Costa et al.

Table 2 Durability Classes (DC) for classifying the untreated and treated wood using the mass loss (ML) values (EN 350, 2016)

Durability class (DC)	Description	Mean ML [%]
1	Very durable	≤ 5
2	Durable	> 5 to ≤ 10
3	Moderately durable	> 10 to ≤ 15
4	Slightly durable	> 15 to ≤ 30
5	Not durable	> 30

Source: EN 350 (2016)

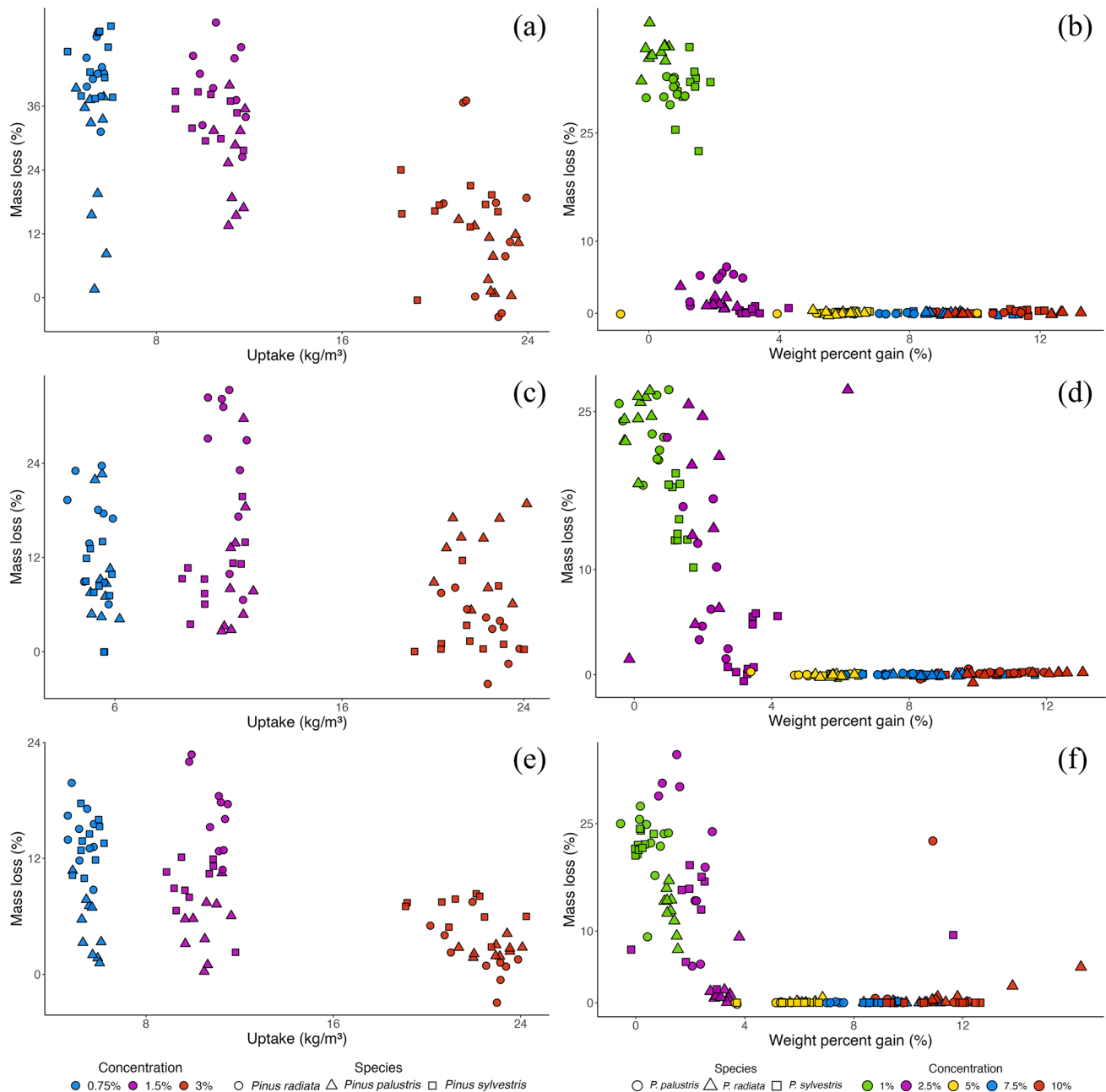


Fig. 1 Interrelationship between treatment intensity and mass loss by fungal decay according to wood preservative concentration ratio (copper-based preservative; on the left) and weight percent gain (modifica-

tion with silicone oil; on the right), where (a) and (b) exposed to *C. puteana*; (c) and (d) exposed to *R. placenta*; (e) and (f) exposed to *A. vaillantii*

2022), capable of surviving in metal-impregnated substrates through mechanisms such as pH regulation. For instance, *A. vaillantii* is particularly aggressive because it acidifies the surrounding environment prior to degradation, which promotes copper solubilization and enhances its own metabolic activity (Humar et al. 2001). However, leaching may counteract this process by increasing the pH, thereby stabilizing copper complexes and reducing fungal activity (Ribera et al. 2017). Since copper-based biocides tend to remain stable

near neutral pH, the leaching process may have indirectly promoted preservative permanence by creating conditions less favourable for fungal development. Overall, these interactions between fungal physiology, pH dynamics, and preservative chemistry help explain the protective behaviour observed across treatments and the concentration-dependent patterns of durability.

In contrast, the silicone oil treatment, showed a clear relationship between product concentration and mass loss

reduction, with higher concentrations consistently enhancing wood durability in all the scenarios. The products protective performance is primarily achieved through hydrophobic and bulking effects (Liu and Cao 2018; He et al. 2019), which physically limit fungal colonization and moisture uptake. In all conditions, treatments with silicone oil (Fig. 1, b, d and f) caused a consistent reduction in fungal decay at WPG values between 2 and 4%. This indicates that the product remained well fixed within the cell wall, reducing water accessibility and consequently biological degradation. The lowest mass losses (%ML) were associated with higher concentrations and were also accompanied by the maintenance of a significant portion of the weight gain (WPG) and cell wall bulking (CWB) values even after leaching, confirming the product's stability. From 2.5% for *C. puteana* (Fig. 1, a) and 5% for the other fungal species (Fig. 1, c and e), mass loss values remained below 5%, and most zero-decay cases occurred above this threshold. This suggests that 5% is the minimum concentration required to ensure full protection of the pine species tested, but in some cases, a 2.5% concentration might be enough to cause the same effect. Despite these differences, for both products, higher concentrations were generally associated with lower mass loss, regardless of the fungal or the wood species tested.

3.2 Durability class

Pearson correlation and principal component analysis (PCA) were performed to summarize the relationships

among treatment parameters and durability indicators. These analyses aimed to identify which variables explained most of the variation in wood durability and to detect interaction effects among treatments, fungi, and concentrations. Pearson's correlation confirmed that, in the case of preservative treatment, uptake (U) and weight loss after leaching (L) were negatively correlated with moisture content (MC) and mass loss (ML), indicating that higher product retention led to lower deterioration. Regarding silicone oil treatment, weight loss after leaching (L), weight percent gain (WPG), and cell wall bulking (CWB), before and after leaching, also exhibited negative correlations with MC and ML, supporting the role of these properties in enhancing wood durability.

PCA reinforced these trends (Fig. 2). In samples treated with the copper-based preservative (Fig. 2a), the first principal component (PC1) explained 58.4% of the total variance and was mainly influenced by U (34.3%) and L (30.5%), whereas the second component (PC2) accounted for 26.2% of the variance and was primarily associated with MC (40.4%) and ML (24.7%). For the silicone oil treatment (Fig. 2b), PC1 explained 61.7% of the variance, was mainly associated with WPG (20.3%), WPG2 (19.6%), and CWB (15.5%), whereas PC2 (12.1%) was primarily influenced by MC (43.3%), CWB2 (19.4%), ML (18.6%), and L (11.3%). Together, these components captured 84.6% and 73.8% of the total variance for the preservative and silicone treatments, respectively, indicating a robust representation of the main trends in the dataset.

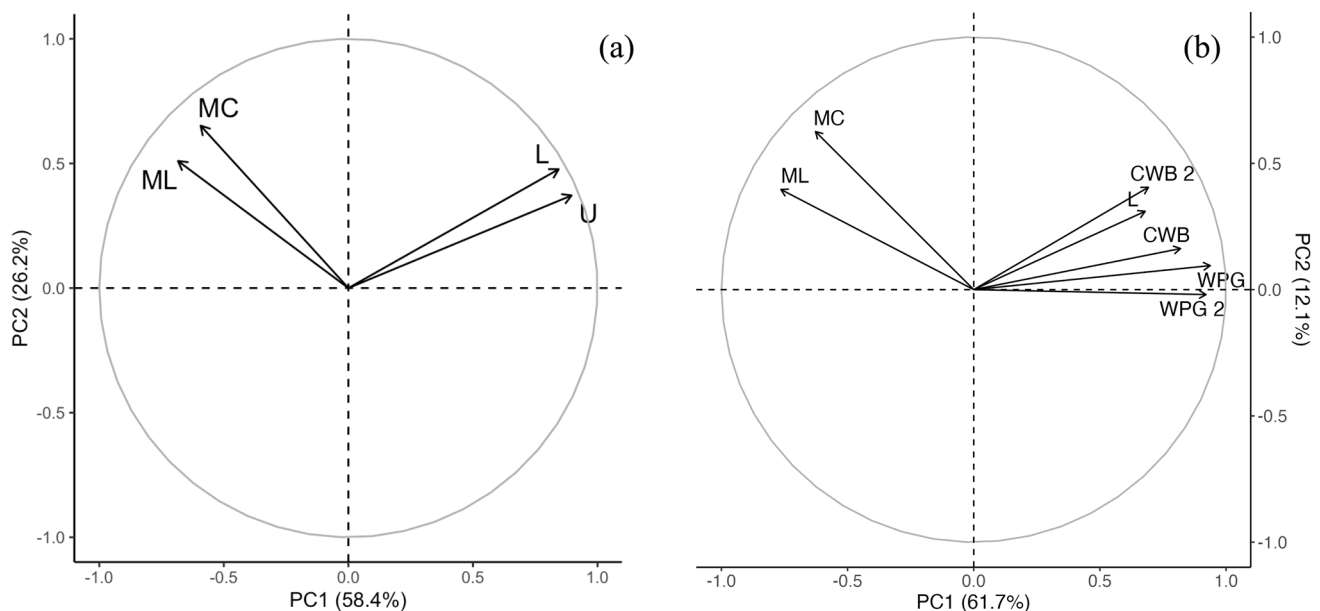


Fig. 2 Loading plot of PC1 and PC2 illustrating the relationship among variables for wood treated with (a) copper-based preservative and (b) silicone oil. Arrows indicate the direction and magnitude of each variable's contribution to the components and positively correlated variables are grouped together. Where: ML: mass loss (%), MC: mois-

ture content (%), L: Weight loss after leaching (%); U: uptake (kg/m³), WPG: Weight percent gain (%), WPG2: Weight percent gain after leaching (%), CWB: cell wall bulking (%), CWB2: cell wall bulking after leaching (%)

Biologically, PC1 represented durability-enhancing properties (U, WPG, and CWB), while PC2 groups involved decay-related factors (MC and ML). The opposing directions of these vectors indicated an inverse relationship, as MC and ML decreased, wood durability increased. The positioning of L closer to durability vectors rather than decay variables is technically consistent, since higher product uptakes resulted in greater absolute leaching values due to excess material in lumens that did not chemically bind to the cell wall but remained measurable as leachable residue. Consequently, samples with greater absorption of these components tended to have higher absolute weight loss after leaching values (L).

Based on the interpretation of PC1 and PC2 as durability- and decay-related components, respectively, a subsequent analysis was conducted to explore whether different experimental factors contributed to the observed variability. The PCA was applied to assess how wood species, fungal strains, and treatment concentration influenced on overall durability (Fig. 3). A substantial overlap among wood species indicated little influence on overall durability regardless the product (Fig. 3a and b). In contrast, decay fungi showed different behavior based on the product use. Regarding silicone oil treatments (Fig. 3d), the clusters overlapped uniformly across the species, while in the preservative treatments (Fig. 3c), *C. puteana* data showed greater dispersion, mainly in the quadrant most influenced by ML and MC (Fig. 2b). This indicates that the preservative was not as efficient in protecting the wood against *C. puteana* as it was for the other two fungal species, resulting in greater mass loss and moisture content under this treatment. Regarding the influence of product concentration, no uniform overlap of ellipses was observed in either case, indicating a tendency toward different efficiency levels among concentrations (Fig. 3e and f). For the preservative treatment, the 3% concentration was predominantly located in the quadrant associated with durability-related components. In contrast, for the silicone oil treatment, this trend became evident from concentrations at 5% and above.

Finally, PCA incorporating EN 350 (2016) durability classes (Fig. 4) confirmed a clear relationship between treatment concentration and wood durability. This pattern reinforces the overall trend observed in previous analyses, demonstrating that increasing the amount of product fixed in the wood directly contributed to greater resistance against fungal decay and higher durability classifications.

In the preservative treatments (Fig. 4, a), the lower concentrations were distributed along the quadrant most influenced by ML and MC, whereas the highest concentration (3%) was concentrated in the quadrant dominated by uptake (Fig. 2, a). This indicates that higher preservative uptakes generally led to lower mass loss, since most of 3%

observations were concentrated in the highest durability class. However, several samples treated with a 3% concentration were also distributed across other durability classes, reflecting variability in treatment effectiveness. This variability can be attributed to the effects of leaching, which can have a stronger influence in this quadrant and may have affected some wood samples. These results demonstrate that higher durability is not always directly correlated with higher product concentrations, as also reported by Temiz et al. (2014) for copper-based preservatives after leaching, where durability varied according to wood species and fungal strain.

In the silicone oil treatments (Fig. 4, b), a clear grouping of concentrations above 5% was observed in the highest durability class (DC-1). Concentrations of 5% and above tended to cluster in the quadrant most influenced by WPG and CWB, suggesting that treatments at or above 5% result in reduced mass loss, and consequently, greater wood durability. However, some treatments with 2.5% also achieved this classification. Based on these observations, it can be inferred that, in general, was the minimum concentration required to achieve the highest durability in the wood species evaluated in this study.

The relationship between concentration and durability class highlights the central role of treatment efficiency in determining wood performance under fungal exposure. In addition to the effects of concentration, the achieved durability largely depended on the stability and fixation of the products to the wood surface, which determine their permanence and protective effectiveness over time. This relationship confirms that better fixation directly contributed to reduce biodegradation and was aligned with higher durability classifications. Overall, these results suggest that the concentrations previously indicated (silicone oil $\geq 5\%$; copper-based preservative = 3%), due to their good performance under laboratory conditions are promising for practical applications, provided their long-term effectiveness is validated in tests simulating real service conditions. Furthermore, these findings demonstrate the potential of such formulations to serve as more sustainable options compared to conventional wood preservatives, which are often associated with environmental contamination. In this context, the results in this study contribute to expand the range of wood protection products aligned with sustainability principles and reduced ecological impact.

4 Conclusion

Both treatments with biocidal and non-biocidal formulations increased the durability of sapwood from *P. palustris*, *P. radiata*, and *P. sylvestris* against brown-rot fungi.

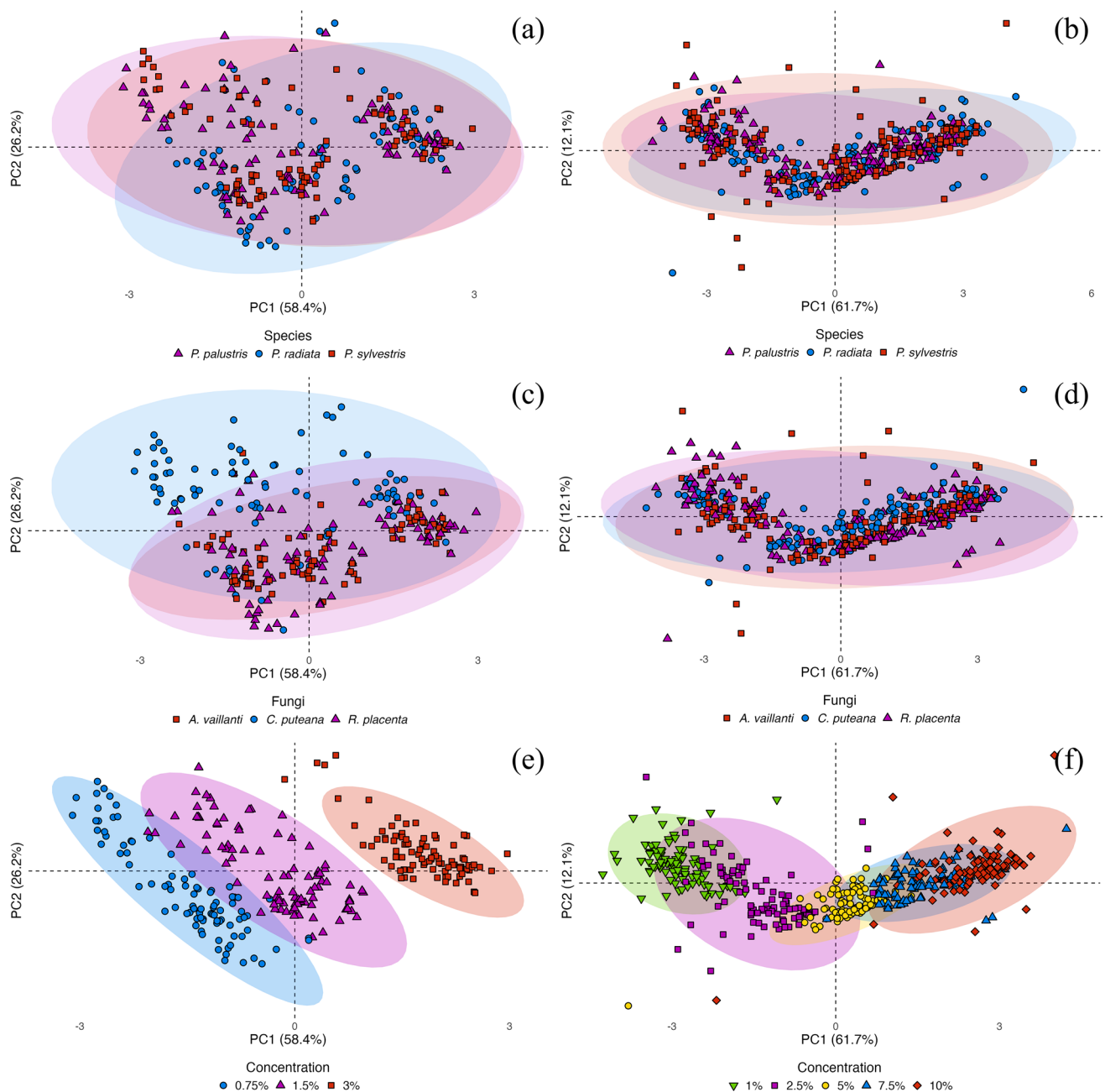


Fig. 3 Score plot illustrating the effects of wood species, fungal species and concentration on copper-based preservative (a, c, e) and silicone oil (b, d, f) treatments

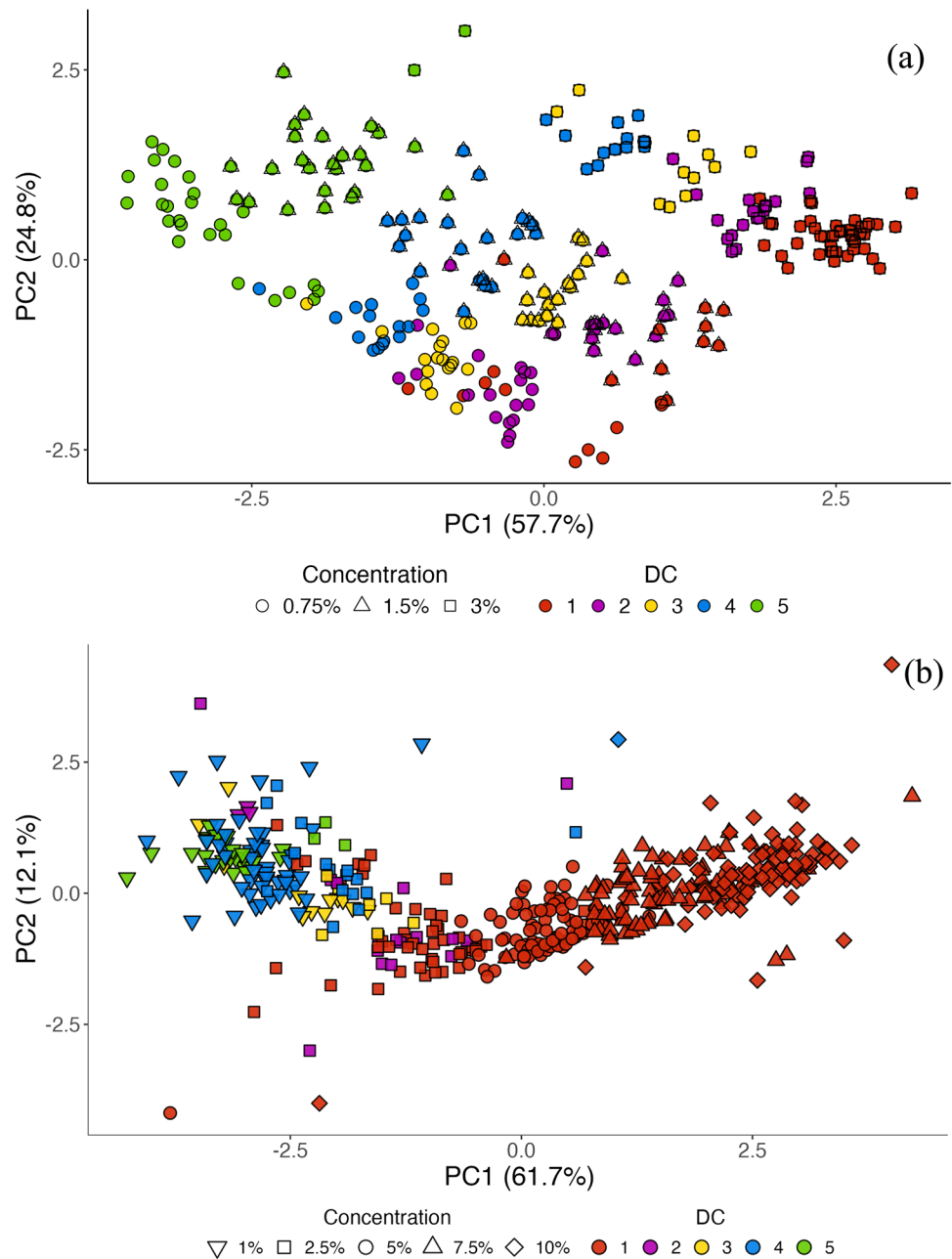
Although no major differences had been observed neither between wood species nor the fungal species of choice, a trend was noted showing that higher treatment concentrations generally led to increased durability. In general, the consistent performance across the tested pine species supports the applicability of the chosen active ingredients for enhancing the durability of treatable pine sapwood sections.

Regarding copper-based preservative treatments, most samples which achieved the highest durability class (DC 1) originated from treatments with the highest concentration.

Nevertheless, the performance of specimens treated with the biocidal formulation of choice was less consistent than expected, as intermediate durability classes (DC 2–3) were assigned to several other samples treated at the highest concentration level.

Silicone oil treatments demonstrated a clear relationship between treatment concentration and the protective effect against decay by brown-rot fungi. Specimens treated at concentrations above 5% predominantly reached the highest durability class (DC 1). Thus, treatments at around 5%

Fig. 4 Score plot of preservative (a) and silicone oil (b) treatment concentrations in relation to durability classes (DC) according to EN 350 (2016) standard



can therefore be considered as the recommended treatment level, as such may guarantee a DC 1 level in treated sapwood specimens. Nevertheless, even samples treated with 2.5% did partly achieve DC 1 levels, suggesting that concentrations between 2.5% and 5% should be further evaluated to determine whether lower treatment levels may assure a DC 1 level of protection. As a next step, the present findings should be validated under field conditions to confirm the effectiveness of the treatment techniques of choice under external environments and in real service conditions.

Acknowledgements The authors thank the National Council for Scientific and Technological Development (CNPq), the Coordination for the Improvement of Higher Education Personnel (CAPES), and the

University of Göttingen for funding this project, and Wood Biology and Wood Products for providing the resources and infrastructure for this research.

Author contributions Tarcila Rosa da Silva Lins, Lukas Emmerich and Holger Militz contributed to the study conception and design. Material preparation and data collection were performed by Tarcila Rosa da Silva Lins and Lukas Emmerich. The first draft of the manuscript was written by Tarcila Rosa da Silva Lins and all authors commented on previous versions of the manuscript. Data analysis was performed by Tarcila Rosa da Silva Lins, Lukas Emmerich and Ricardo Lima de Souza. All authors read and approved the final manuscript.

Funding The Article Processing Charge (APC) for the publication of this research was funded by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) (ROR identifier:

00x0ma614).

Data availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interest The authors declare no conflict of interest.

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

- Baysal E, Deveci I, Turkoglu T, Tokar H (2017) Thermal analysis of oriental beech sawdust treated with some commercial wood preservatives. *Maderas Ciencia y Tecnología* 19(3):329–338. <https://doi.org/10.4067/S0718-221X2017005000030>
- Brischke C, Alfredsen G (2022) Biological durability of pine wood. *Wood Mater Sci Eng* 17(6):1050–1064. <https://doi.org/10.1080/17480272.2021.2012475>
- Brischke C, Bollmus S, Emmerich L (2024) Comparative durability tests of preservative-treated and chemically modified wood – Assessment and classification on the basis of different decay tests. *Eur J Wood Wood Product* 82(4):1083–1094. <https://doi.org/10.1007/s00107-024-02034-2>
- Civardi C, Schubert M, Fey A, Wick P, Schwarze FWMR (2015) Micronized copper wood preservatives: Efficacy of ion, nano, and bulk copper against the brown rot fungus *Rhodonia placenta*. *PLoS ONE*. <https://doi.org/10.1371/journal.pone.0142578>
- Costa LG, Brocco VF, Paes JB, Kirker GT, Bishell AB (2022) Biological and chemical remediation of CCA treated eucalypt poles after 30 years in service. *Chemosphere* 286:131708. <https://doi.org/10.1016/j.chemosphere.2021.131708>
- Emmerich L, Altgen M, Rautkari L, Militz H (2020) Sorption behavior and hydroxyl accessibility of wood treated with different cyclic N-methylol compounds. *J Mater Sci* 55(36):16561–16575. <https://doi.org/10.1007/s10853-020-05224-y>
- Emmerich L, Ehrmann A, Brischke C, Militz H (2021a) Comparative studies on the durability and moisture performance of wood modified with cyclic N-methylol and N-methyl compounds. *Wood Sci Technol* 55(5):1531–1554. <https://doi.org/10.1007/s00226-021-01303-8>
- Emmerich L, Bleckmann M, Strohbusch S, Brischke C, Bollmus S, Militz H (2021b) Growth behavior of wood-destroying fungi in chemically modified wood: Wood degradation and translocation of nitrogen compounds. *Holzforschung* 75(9):786–797. <https://doi.org/10.1515/hf-2020-0210>
- European Committee for Standardization (2016) EN 350: Durability of wood and wood-based products – Testing and classification of the durability to biological agents of wood and wood-based materials. CEN, Brussels
- European Committee for Standardization (2020) EN 84: Durability of wood and wood-based products – Accelerated ageing of treated wood prior to biological testing – Leaching procedure. CEN, Brussels
- European Committee for Standardization (2021) EN 113-2: Durability of wood and wood-based products – Test method against wood destroying basidiomycetes – Part 2: Assessment of inherent or enhanced durability. CEN, Brussels
- Gérardin P (2016) New alternatives for wood preservation based on thermal and chemical modification of wood—a review. *Ann For Sci* 73(3):559–570. <https://doi.org/10.1007/s13595-015-0531-4>
- He Z, Qu L, Wang Z, Qian J, Yi S (2019) Effects of zinc chloride–silicone oil treatment on wood dimensional stability, chemical components, thermal decomposition and its mechanism. *Sci Rep* 9(1601). <https://doi.org/10.1038/s41598-018-38317-5>
- Humar M, Petrič M, Pohleven F (2001) Changes of the pH value of impregnated wood during exposure to wood-rotting fungi. *Holz als Roh- und Werkst* 59(4):288–293. <https://doi.org/10.1007/s001070100212>
- Humar M, Žilindra D, Pohleven F (2007) Influence of wood species, treatment method and biocide concentration on leaching of copper–ethanolamine preservatives. *Build Environ* 42(2):578–583. <https://doi.org/10.1016/j.buildenv.2005.09.021>
- Kängsepp K, Larnøy E, Meier P (2011) Leaching of commonly used impregnation agents affected by wood properties. *Norsk Institutt for Bioøkonomi*
- Kurkowiak K, Emmerich L, Militz H (2021) Wood chemical modification based on bio-based polycarboxylic acid and polyols – status quo and future perspectives. *Wood Mater Sci Eng* 17(5):1–15. <https://doi.org/10.1080/17480272.2021.1964233>
- Liu Z, Cao J (2018) Fabrication of superhydrophobic wood surface with a silica/silicone oil complex emulsion. *Wood Res* 63(2):353–364
- Mai C, Militz H (2004) Modification of wood with silicon compounds. Inorganic silicon compounds and sol–gel systems: A review. *Wood Sci Technol* 37(5):339–348. <https://doi.org/10.1007/s00226-003-0206-4>
- Mangini TdeS, Candaten L, Nardini C, Minini D, Eloy E, Trevisan R, Kulczynski SM (2025) Biological resistance and chemical properties of wood from an agroforestry system. *Holzforschung*. <https://doi.org/10.1515/hf-2025-0009>
- Ribeiro A, Kroetz B, Bertoldo LA, Abrao T, Parreira P, Santos MJ (2025) Diffusion of potentially toxic elements from CCA-treated wood into clayey and sandy Brazilian soils. *J Hazard Mater* 495:138703. <https://doi.org/10.1016/j.jhazmat.2025.138703>
- Ribera J, Fink S, Bas MdC, Schwarze FWMR (2017) Integrated control of wood destroying basidiomycetes combining Cu-based wood preservatives and *Trichoderma* spp. *PLoS ONE* 12(4):e0174336. <https://doi.org/10.1371/journal.pone.0174336>
- Sandberg D, Kutnar A, Karlsson O, Jones D (2022) Wood modification technologies: principles, sustainability, and the need for innovation, 1st edn. CRC. <https://doi.org/10.1201/9781003084806>
- Schultz TP, Nicholas DD (2007) Totally organic wood preservative for exterior residential applications. In: Barnes HM (ed) *Wood Protection*. Forest Products Society, pp 289–294
- Temiz A, Alfredsen G, Yildiz UC, Gezer ED, Kose G, Akbas S, Yildiz S (2014) Leaching and decay resistance of alder and pine wood treated with copper-based wood preservatives. *Maderas Ciencia y Tecnología* 16(1):63–76. <https://doi.org/10.4067/S0718-221X2014005000006>

Treu A, Larnøy E, Militz H (2011) Process related copper leaching during a combined wood preservation process. *Eur J Wood Wood Product* 69(2):263–269. <https://doi.org/10.1007/s00107-010-0416-0>

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