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Articles

Furfurylated *Pinus* sp. wood resistance to the action of xylophagous fungus *Rhodonia placenta* in laboratory

Resistência da madeira furfurilada de *Pinus* sp. a ação do fungo xilófago *Rhodonia placenta* em laboratório

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ABSTRACT

Although wood is a renewable resource, it is subject to deterioration processes that require preservative treatment applications to increase its durability. Despite its several advantageous properties, pine wood is susceptible to many wood-eating organisms; therefore, it is essential applying preservatives to optimize its use. Accordingly, the aim of the present study ia to assess the efficiency of pine wood treatment with furfuryl alcohol to improve its resistance against wood-eating fungus *Rhodonia placenta* under laboratory conditions. Seventy-five (75) specimens were produced and subjected to five treatments, including the control, fifteen replicates and four different FA concentrations (10%, 25%, 50% and 100%). The samples were subjected to *R. placenta* under laboratory conditions. All FA concentrations were capable of increasing pine wood resistance against this fungus; it significantly reduced mass loss in comparison to untreated wood. In conclusion, furfuryl alcohol protected *Pinus sp*. wood against *R. placenta* action under laboratory conditions, at any tested concentrations.

Keywords: Wood treatment; Impregnation; Furfuryl alcohol; Brown rot disease

RESUMO

A madeira embora seja um recurso renovável, está sujeita a processos de deterioração, demandando a aplicação de tratamentos preservativos para aumentar sua durabilidade. Apesar de suas diversas propriedades vantajosas, a madeira de Pinus apresenta susceptibilidade a diversos organismos xilófagos, sendo essencial a aplicação de preservativos para a utilização otimizada. Diante do exposto, este trabalho objetiva avaliar a eficiência do tratamento da madeira de *Pinus* sp. com álcool furfurílico sobre à agregação de resistência ao fungo xilófago *Rhodonia placenta*, em condições de laboratório. Foram produzidos 75 corpos de prova, divididos em cinco tratamentos, incluindo controle, de quinze repetições, com quatro concentrações distintas de AF (10%, 25%, 50% e 100%). As amostras foram submetidas à ação de *R. placenta* em condições laboratoriais. Todas as concentrações de AF demonstraram capacidade de aumentar a resistência da madeira de Pinus de maneira equivalente contra o fungo, reduzindo significativamente a perda de massa em comparação com a madeira não tratada. Conclui-se que o álcool furfurílico, em qualquer das concentrações avaliadas, confere proteção à madeira de *Pinus* sp. contra a ação de *R. placenta* sob condições laboratoriais.

Palavras-chave: Tratamento de madeira; Impregnação, Álcool furfurílico; Podridão parda

1 INTRODUCTION

Pinus sp. reforestation leads to wood featured by physical and mechanical properties attractive to the timber market; therefore, it is a sustainable alternative to native-forest exploitation. However, although it is broadly used in furniture manufacturing and construction structures (Ladeira *et al*., 2018; Vidal *et al*., 2015), it is a highly soft, porous and low-density wood. It makes wood quite susceptible to the action of deteriorating organisms like xylophagous fungi (Schulz *et al*., 2020).

Due to its low natural durability, pine wood requires treatments aimed at adding resistance against wood-eating organisms in order to optimize its use (Gallio *et al*., 2019; Schulz *et al*., 2019; Yang *et al*., 2023). Thus, chemical wood treatment has been the main strategy adopted by industries (Lepage *et al*, 2017; Trevisan *et al*., 2020). However, research has been implemented to develop alternative methods aimed at increasing wood durability, given the several questions that have emerged over the years, mainly those regarding inputs' environmental safety. These strategies are efficient and account for low environmental impact (Cruz-Lopes *et al*. 2025; Santos *et al*. 2022; Appel *et al*. 2006).

Accordingly, furfurylation is one of the most promising methods to add biological resistance to wood, although it has not yet been commercially explored in Brazil. It consists in using furfuryl alcohol (FA) to fill up intercellular spaces with furfuryl resin. Furfuryl alcohol (FA) is a material based on monomers that polymerize inside the impregnated wood; furthermore, this compound comes from furfural (Mariscal *et al*., 2016; Schulz *et al*., 2019; Zelinka *et al*., 2022), mainly from processing sugarcane and maize industry waste.

Furfuryl wood is less susceptible to the action of several xylophagous organisms, such as fungi (Skrede *et al*., 2019). It is explained by the presence of polymerized furfuryl resin between wood anatomical elements, which also makes wood more dimensionally stable, physically resistant and present lower hygroscopicity (Lande *et al*., 2004a, Sandberg *et al*., 2018).

Accordingly, the aim of the current study was to assess the efficiency of treating Pinus sp. wood with furfuryl alcohol to enhance its resistance to xylophagous fungus Rhodonia placenta under laboratory conditions.

2 METHODOLOGY

Pine wood came from two felling trees that were grown in the Federal Rural University of Rio de Janeiro (UFRRJ) campus. Boards and battens were cut from the trunk, from the log's external region, and they were used to produce 75 test specimen measuring 2.5 in width x 2.5 in length x 0.9 cm in thickness, as recommended by AWPA E10-16.

Solutions comprising four different FA concentrations were prepared to chemically Treat the samples. These solutions encompassed furfuryl alcohol (FA), ethyl alcohol, citric acid and water. Ethyl alcohol was used for catalytic purposes and citric acid was applied for anti-leaching purposes, based on authors such as Schulz *et al*. (2019), or as a catalyst, according to Lande *et al*. (2004a), Pilgård *et al*. (2010) and Thygesen *et al*. (2020). Water was used to homogenize the solutions. It is essential observing that citric acid is an agent capable of giving fungal resistance to wood, as stated by Cruz-lopes, *et al*. (2025); therefore, its role exceeds anti-leaching and catalytic functions.

Table 1 – Composition of preservative solutions used for *Pinus sp.* wood furfurylation

Tratament	FA* (%)	EA* (%)	Water (%)	CA* (%)
Control	-	-	-	-
10%	10	80	5	5
25%	25	65	5	5
50%	50	40	5	5
100%	100	-	-	-

Source: Authors (2025)

In where: *FA= Furfuryl alcohol; *EA = Ethyl alcohol; *CA = Citric acid.

The fresh weight of all samples was measured on analytical scale after their acclimation until reaching constant weight at 70 °C. Wood soaking in the solution was achieved through sample submersion in 2-liter Erlenmeyer flasks, as recommended by Skrede *et al*. (2019) - Samples rested under this condition for 30 days. This procedure allowed wood saturation by the solutions described in Table 1. The specimens were weighed again right after saturation and taken to oven at temperature of 70 °C, for 7 days, in the laboratory, to polymerize the furfuryl resin. Their weight was measured again when they reached constant weight under the aforementioned condition. Weight values were used to calculate polymer gain percentage (PGP), Equation (1), absorption (AB), Equation (2), and preservative retention in each sample (RT), Equation (3), according to the following equations:

$$PGP = [(PP - OS) / OS] * 100 \quad (1)$$

$$AB = (PST - OS) / V \quad (2)$$

$$PGP = [(PP - OS) / OS] * 100 \quad (3)$$

wherein: PGP = polymer gain percentage (%); PP = polymerized sample weight (gr); OS = dry sample weight (gr); PST = saturated sample weight (gr); V = sample volume (cm^3).

AWPA E10-16 standard guidelines were used to perform the experiment with fungus *R. Placenta*. In order to do so, 38 glass bottles (500 ml) with screw caps were used in the experiment. They were filled with 180 g soil and 40 ml distilled water.

These bottles received two *Pinus* slides, each (3 cm x 3 cm) and, subsequently, they were sterilized in laboratory autoclave. The *Pinus* slides were, then, inoculated with fungus *R. Placenta* from pure cultures kept in PDA culture medium. This procedure was performed in horizontal laminar flow hood.

Fungi were placed on pine slides to develop for thirty days. Two treated and sterilized specimens from each bottle were placed on these slides. This stage was also conducted in laminar flow hood. The samples remained subjected to *R. placenta* action for four months. Subsequently, they were cleaned and acclimated at 70°C until reaching constant weight in order to be weighed again. The mass loss percentage caused by this fungus' action was calculated by subtracting the value measured before the samples were subjected to *R. placenta* from the weight measured after they were subjected to it. These values were used to classify the wood into different strength classes (Table 2).

Table 2 – Wood strength class classification criteria based on mass loss (AWPA E30-16)

Class of resistance	Average weight loss (%)
Highly resistant	0-10
Resistant	11-24
Moderately resistant	25-44
Not resistant or perishable	45 or above

Source: Authors (2025)

Data analysis was carried out in BioEstat 5.0 software (Ayres *et al*. 2007). Therefore, normality was assessed through Lilliefors test at 5% significance. Tukey test was run at 5% significance whenever normality was recorded. Kruskal-Wallis test was applied to non-normal data with Dunn's post-test (at 5% significance) to analyze mean-rank variances.

3 RESULTS

FA treatment applied to *Pinus sp*. wood led to different furfuryl resin incorporation into the samples. Therefore, PGP (polymer gain percentage) statistically differed depending on the FA concentrations used in the wood (Table 3). Applying 50% FA led to significantly higher PGP than other treatments. It wass also clear that 25% FA also allowed significantly higher PGP than pure FA.

Table 3 – Polymer gain percentage (PGP), absorption and retention (g/cm³) of *Pinus sp*. wood treated with furfuryl alcohol at four different concentrations

Tratament	PGP (%)	Absorption (g/cm³)	Retention (g/cm³)
Control	---	---	---
10 %	12 ± 5 d	1,111 ± 0,09 b	0,102 ± 0,043 d
25 %	25 ± 5 b	1,406 ± 0,06 a	0,202 ± 0,030 b
50 %	39 ± 6 a	1,446 ± 0,09 a	0,334 ± 0,043 a
100 %	16 ± 3 c	1,391 ± 0,13 a	0,139 ± 0,036 c

Source: Authors (2025)

In where: * Different letters, between bars, express statistically significant differences (Tukey, 5% significance level).

According to this outcome, additives used for diluted FA, ethyl alcohol, water and citric acid solution preparation can increase furfuryl resin polymerization efficiency in wood in comparison to wood treated with pure FA solutions (additive free). Thus, the furfuryl resin polymerization process is associated with solution pH; furthermore, this process proves to be more efficient with more acidic solutions (Coimbra *et al*., 2022). Therefore, citric acid using may have influenced the process to achieve higher PGP values. However, such significant pure FA solution polymerization maximization was not observed at 10% dilution (Table 3).

It is worth noticing that, although solution dilutions had influenced PGP, solution absorption by the wood was mostly unaffected by dilution, since the amount of absorbed product was almost the same under all treatments. Only the 10% dilution recorded significantly lower absorption than the other dilutions (Table 3). Retention expresses the amount of product retained in the wood after its acclimation; it was similar to what was observed for PGP values, which points towards the great influence of preservatives' liquid dilutions. Therefore, concentrations of 25% and 50% were the most efficient for solution retention in the wood, since they led to values proportional to those observed for PGP.

Schulz *et al*. (2019) furfurylated *Pinus elliotti* wood under vacuum-pressure at 5% citric acid and Fa concentrations of 10%, 25% and 50%. They recorded the following PGP values: 4.28%. 8.55% and 7.01%, respectively. These values were lower than those observed in the present study. Assumingly, the lower effectiveness of FA impregnation inside the cell wall caused by the vacuum-pressure process is one explanation for the herein adopted longer saturation process.

On the other hand, Lande *et al*. (2004b) furfurylated *Pinus sylvestris* wood by using citric acid and cyclic carboxylic anhydrides as catalysts, at FA concentrations of 92%, 48%, 30% and 15%. They recorded 120%, 50%, 29% and 11% PGP, respectively, and these values are higher than those recorded in the present study. They emphasized that the observed PGP percentage values can be related to *P. sylvestris* wood low density and high porosity, as well as to the catalysts used for solution preparations, mainly carboxylic anhydride, which differs from that used in the current study.

Although the wood treatment based on different FA dilutions led to different PGP values, this process did not account for significant difference in the aggregation of *Pinus sp*. wood resistance against fungus *R. placenta*. Thus, fresh wood was moderately resistant to this fungus, whereas wood treated with FA, at any tested concentration, became very resistant (Table 4).

Table 4 – Resistance class of *Pinus sp*. wood treated with furfuryl alcohol, at four concentrations, subjected to *Rhodonia placenta* actions for four months

Tratament	Class of resistance
Natural wood	Moderately resistant
10%	Highly resistant
25%	Highly resistant
50%	Highly resistant
100%	Highly resistant

Source: Authors (2025)

The recorded result can be linked to several factors, among them wood intracellular space filling by furfuryl resin, as shown by Thygesen *et al*. (2021). They observed that cell lumen was filled with furfuryl resin through confocal laser microscopy analysis applied to fresh and furfurylated *Pinus radiata* wood. Therefore, this filling process reduces hygroscopicity and turns wood into a less favorable substrate for the development of most xylophagous fungi (Lande *et al.*, 2004a; Lande *et al.*, 2004b; Pilgård *et al*., 2010; Beck *et al*., 2019; Mayowa *et al.*, 2023).

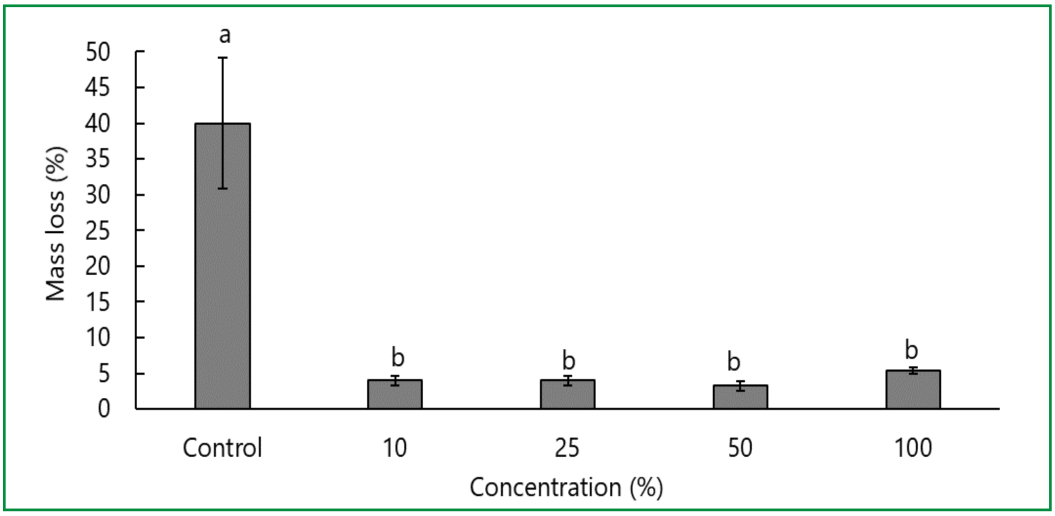
Therefore, FA non-toxic action on these fungi reduces water supply to these organisms and it enhances wood biological resistance. Therefore, there is consensus that the fungal inhibition mechanism in furfurylated wood is also related to the aforementioned featured, as reported in several studies, such as those by Esteves *et al*. (2010), Sejati *et al.* (2016), Mantanis (2017).

On the other hand, a different aspect can also act in the aggregation of furfurylated wood resistance against the action of *R. placenta*, namely: cell wall chemical composition change. Accordingly, Lande *et al*. (2004a, 2008), Nordstierna *et al*. (2008), Sejati *et al*. (2016) and Gallio *et al*. (2019) showed the connection between furfuryl resin and wood cell wall, and it causes changes in wood chemical composition, which would delay its polymeric component degradation by fungi (Skrede *et al*., 2019).

Skrede *et al*. (2019) observed that this fungus' gene expression was affected when it comes to enzyme production in furfurylated *Pinus radiata* wood subjected to the action of fungus *R. placenta*. They showed that the production of enzymes such as oxidoreductase, and others presenting hydrolytic function, was delayed in comparison to this fungus' action in fresh wood. Similar outcomes were shown by Alfredsen *et al*. (2016). Skrede *et al*. (2019) and Alfredsen *et al*. (2016) reports allowed pointing out that the present results can be also related to these gene mechanisms, which affect the production of enzymes used in wood polymeric component degradation processes.

Similar to the increased resistance class of furfurylated *Pinus sp*. wood, the treatment carried out with 10% FA recorded mass loss statistically equal to that of wood treated with solutions presenting higher FA concentrations (Figure 1). This finding highlights that solutions showing lower FA concentrations, despite significantly influencing PGP reduction, as previously discussed, also lead to effects similar to those recoded for solutions presenting higher concentrations when it comes to the resistance aggregation recorded for *Pinus sp*. wood exposed to the action of *R. placenta*. Therefore, solutions with lower FA concentrations can provide efficient resistance aggregation against this fungus and account for savings regarding the impregnating product.

Figure 1 – Mass loss percentage of *Pinus sp*. wood treated with furfuryl alcohol at different four concentrations, subjected to the action of xylophagous fungus *R. placenta* for four months



Source: Authors (2025)

In where: Different letters, between bars, express statistically significant differences (Dunn, 5% significance level).

The literature points out some similar results and results different from the herein observed ones about reduction in the mass loss of furfurylated wood subjected to the action of xylophagous fungi. Esteves *et al*. (2010) observed 1.1% mass loss for *Pinus pinaster* wood at 70% furfurylation provided by *R. placenta*, and this finding is similar to that recorded in the present study. According to Skrede *et al*. (2019), *Pinus radiata* wood furfurylated at FA concentrations of 10%, 40% and 70% recorded 42.5%, 34.6% and 16.0% mass loss, respectively, when it was subjected to the action of *R. placenta*.

Mass loss values presented by Skrede *et al*. (2019) were higher than those observed in the current study, and it can be explained by the catalyst type used to compose the preservative solutions. Therefore, the citric acid used in the present study to catalyze the polymerization reaction provided strong evidence that it inhibits the action of fungus *R. placenta*. Cruz-Lopes *et al*. (2025) used citric acid solutions diluted at concentrations of 5%, 10% and 15% to treat *Pinus pinaster* wood and observed that all treatments carried out at any of these concentrations added significant resistance to wood against action of fungus *R. placenta*.

The present results recorded significant reduction in mass loss in comparison to fresh wood and it can be explained by the catalyst type used to prepare the FA solutions. Thus, the study hypothesis advocated that citric acid may have acted in the process, in addition to catalyze the polymerization reaction of the furfuryl resin as agent capable of improving wood resistance to fungus *R. placenta*, in synergy with furfuryl alcohol.

4 CONCLUSIONS

Pinus sp. fresh wood is moderately resistant to fungus *Rhodonia placenta* under laboratory conditions. The wood became highly resistant when it is impregnated with furfuryl alcohol at any of the tested concentrations.

The furfuryl alcohol concentration applied to *Pinus sp*. wood influenced the amount of furfuryl resin incorporated into the wood, but it had no effect on fungus' inhibition the efficiency; therefore, the lowest assessed concentration (10%) recorded efficiency similar to that of the highest tested concentrations.

The additives adopted to carry out the dilutions, namely: ethyl alcohol, water and citric acid, improved polymerization in relation to impregnation with pure furfuryl alcohol, and it led to higher furfuryl resin incorporation percentages in *Pinus sp*. Wood.

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Artigo Premiado no VI CBCTEM

Com o objetivo de incentivar a disseminação do conhecimento e ampliar a visibilidade das pesquisas na área de Tecnologia de Produtos Florestais, a revista Ciência Florestal premiou, com a publicação em seu periódico, trabalhos científicos apresentados durante o VI Congresso Brasileiro de Ciências e Tecnologia em Engenharia Madeireira (CBCTEM), realizado de 16 a 18 de outubro de 2024, na cidade de Pelotas, RS. O evento foi promovido pelo curso de Engenharia Industrial Madeireira da Universidade Federal de Pelotas (UFPel).

Um dos artigos contemplados foi **Resistência da madeira furfurilada de *Pinus* sp. a ação do fungo xilófago *Rhodonia placenta* em laboratório**, de autoria de João Vinicius Lourenço Coelho Netto, Henrique Trevisan, Vinicius José FernandesI e Matheus Jardim dos Santos, da Universidade Federal Rural do Rio de Janeiro.

A Equipe Editorial da revista Ciência Florestal parabeniza os autores e autoras pela conquista, bem como o coordenador geral do evento, Professor Dr. Leonardo da Silva Oliveira, e o Comitê Científico do VI CBCTEM, pelo sucesso da iniciativa.

Awarded Article at the VI CBCTEM

Aiming to encourage the dissemination of knowledge and increase the visibility of research in the field of Forest Products Technology, the journal Ciência Florestal awarded, with publication in its journal, scientific papers presented during the VI Brazilian Congress on Science and Technology in Wood Engineering (CBCTEM), held from October 16 to 18, 2024, in the city of Pelotas, RS. The event was promoted by the Wood Industrial Engineering program at the Federal University of Pelotas (UFPel).

One of the selected articles was **Furfurylated *Pinus* sp. wood resistance to the action of xylophagous fungus *Rhodonia placenta* in laboratory**, authored by João Vinicius Lourenço Coelho Netto, Henrique Trevisan, Vinicius José FernandesI e Matheus Jardim dos Santos, da Universidade Federal Rural do Rio de Janeiro.

The Editorial Team of the Ciência Florestal journal congratulates the authors for this achievement, as well as the general coordinator of the event, Professor Dr. Leonardo da Silva Oliveira, and the Scientific Committee of the VI CBCTEM, for the success of the initiative.

Data Availability Statement:

Datasets related to this article will be available upon request to the corresponding author.

Evaluators in this article:

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