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ORIGINAL ARTICLE

Effects of tannin-geopolymer impregnation on wood: leachability, biodegradation resistance and mechanical properties

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Abstract

Geopolymers have elicited significant attention in the field of construction and building materials due to their enhanced durability, physical load-bearing ability and chemical resistance. This study investigates the effects of geopolymer impregnation on wood, together with commercial tannin-rich bark extract Colatan GT10, which, by itself, preserves wood against decay but leaches out once the wood is exposed to water. The efficacy of the treatments is evaluated through attenuated total reflectance Fourier transform infrared (ATR FTIR) spectroscopy, mechanical testing, decay resistance assessment (EN 113) and leachability analysis (EN 84). The results showed that the two-step tannin-geopolymer impregnation improved the durability of wood against wood decay fungi. The mechanical properties of the treated wood specimen were not different from that of the untreated controls, and the performance of the treated wood specimen was retained after the leaching test. The FTIR revealed that the absorbance of tannin at 10 and 5% treatments was reduced after leaching, indicating the leachability of tannin. The combination of tannin at 5% with subsequent geopolymer at 4% treatment yielded the best performance, showing no significant change in absorbance before and after the leaching test. Overall, this study highlights the potential of combining tannin and geopolymer impregnation treatments to enhance the performance of wood in terms of fixation, leachability and wood decay resistance. These findings contribute to the development of a durable wood material for various applications, such as outdoor construction, where resistance to decay is a critical factor.

1 Introduction

The use of wood as a construction material is increasing and this trend is expected to continue, driven by growing environmental awareness. Due to this awareness, new technologies are being implemented in construction materials design to promote aspects of environmental sustainability. Unlike non-renewable materials, such as concrete and steel, wood and wood-based materials are renewable resources that provide good mechanical properties for structures (Ding et al. 2022; Gao et al. 2023). Even partial replacement of steel and concrete with wood has the potential to reduce the carbon footprint of construction sector by approximately 50% (Romagnoli et al. 2019).

Portland cement, one of the main building materials used today, is recognised as a significant contributor to carbon dioxide emissions due to the high energy requirements and substantial emissions during the manufacturing process (Huang et al. 2020). In recent decades, numerous studies have highlighted the role geopolymers could have as an alternative to Portland cement (Provis 2009; Zhang et al. 2016). Geopolymers are composed of inorganic aluminosilicate-based materials, such as fly ash and clay, mixed with alkaline activators like sodium hydroxide or potassium hydroxide to create a highly reactive mixture (Fernandez-Jimenez et al. 2008). The advantage of geopolymers is that some of these constituents can be sourced from recycled materials, such as geopolymer waste (Hattaf et al. 2021) and recycled aggregates derived from waste concrete recycling and energy sector (Wongsa et al. 2020a, b; Wongsa et al. 2020a, b), which reduces the possible negative impact of this material on the environment.

Geopolymers are highly resistant to biological degradation and thermal stress (Morsy et al. 2019). They also

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possess favourable mechanical properties, enabling them to withstand high loads and stresses (Tchakouté et al. 2017; Lin et al. 2021). Research on geopolymer on various applications such as building materials (Degefu et al. 2023), coatings (Aguirre-Guerrero et al. 2017), fireproofing materials (Ding et al. 2017; Dal Pozzo et al. 2019) and composites with small amounts of lignocellulosic or synthetic fibres from 0.5 up to 15 wt% (Masi et al. 2015) highlight its versatility. These additions improve physical and mechanical properties, as demonstrated by Rodríguez-Espejel et al. (2022), who incorporated agro-lignocellulosic residues, such as husk, as fillers. Others have also investigated the use of geopolymers as adhesives and binders (Zaetang et al. 2015; Shalbafan et al. 2017; Vafaei and Allahverdi 2017; Ye et al. 2020).

There is a growing interest in using wood as a sustainable building material resource. However, wood structures' susceptibility to fungal decay remains a significant concern. In terrestrial ecosystems with temperate climates, wood decomposition is primarily caused by white-rot, brown-rot and soft-rot fungi, which are the steps in the carbon cycle (Björdal et al. 1999; Broda 2018). Chemical treatments and wood modification techniques (Sandberg et al. 2017) are used to slow the deterioration of wood caused by decay fungi. Nevertheless, many preservation methods still have significant environmental drawbacks and have been banned in Europe, including the use of creosotes (Hiemstra et al. 2007) and chromated copper arsenate (Liu et al. 2018). New copper-based preservatives, such as copper azole (CA), alkaline copper quaternary (ACQ), micronized copper (MCQ), copper dimethyl-dithio-carbamate (CDDC), ammoniacal copper citrate (CC), and Cu-HDO (bis-(N-cyclohexyldiazeniumdioxy)-copper), have been introduced as alternatives (Cao and Kamdem 2004; Lin et al. 2009). However, these alternatives may not fully resolve issues related to toxicity and the metal leachability. With the expected increase in wood usage (FAO 2022) and the implementation of more stringent legislation in the construction industry, the search for novel bio-based preservatives has become a critical challenge in modern wood science. Finding solutions that meet both environmental and performance criteria will be essential as wood continues to play a larger role in sustainable construction practices.

Bio-based wood preservatives, including pyrolytic oil distillates (Shiny et al. 2017), monoterpenes (Zhang et al. 2016), propolis extracts (Woźniak et al. 2020), lignin (Chirkova et al. 2011; Andeme-Ela et al. 2021), mistletoe (Yildiz et al. 2020) and tannins (Tondi et al. 2015), have demonstrated effectiveness as inhibitors of wood-decaying fungi; however, the effective antifungals are often water-soluble molecules, which leads to easy leaching and removal from wood, especially when subjected to outdoor exposure. Previous studies have aimed to chemically bind caffeine, through thermal modification (Kwaśniewska-Sip et al. 2019), and tannins into wood (Thevenon et al. 2009; Tondi et al. 2012, 2015). López-Gómez et al. (2022) investigated how different wood species perform on tannin fixation using thermal modification and oil-based varnish treatment, showing that the performance of these methods varies depending also on the wood species. Oil treatments have been previously used to reduce the leaching of chemicals from wood, such as copper azoles (Can and Sivrikaya 2017). These procedures are not applied on a commercial scale, highlighting the need for alternative methods that will bring a new possibility of substituting the current synthetic preservatives with non-synthetic alternatives.

The aim of the present study is to prevent the leaching of tannins from wood using a two-step impregnation treatment utilizing metakaolin-based geopolymer, improving the decay resistance after leaching exposure. The evaluation focuses on biodegradation resistance, leachability and mechanical properties. The findings of this study contribute to a better understanding of the interaction between geopolymers and tannin-treated wood.

2 Materials and methods

2.1 Wood specimens

Scots pine (*Pinus sylvestris* L.) sapwood obtained from the Kerimäki sawmill (Finland) was cut into specimens measuring $40 \times 10 \times 5$ mm^3, free of defects and with longitudinal faces parallel to the grain direction. Afterwards, various treatments with different concentrations were applied, including tannin impregnation, geopolymer impregnation, tannin with subsequent geopolymer impregnation and untreated specimens as control. The number of replicates per treatment was 80.

2.2 Tannin and geopolymer impregnation

The wood specimens were treated with either tannin-rich bark extracts (Colatan GT10) or geopolymer, as well as in combined treatment. In combined treatments, specimens were first impregnated with 5% and 10% Colatan GT10 solution, followed by drying, and subsequently subjected to a secondary impregnation using a diluted geopolymer solution at concentrations of 2% and 4% (w/w as Milli-Q water solution).

Geopolymers were made of metakaolin (Metaver O) purchased from Newchem GmbH (Austria). Sodium hydroxide (Fisher Scientific, 99.4%) and sodium silicate solution (Sigma-Aldrich, SiO_2: 26.5%, Na_2O: 10.6%) were used as an alkaline activator. The activation solution was subsequently mixed with the calculated quantities of metakaolin, with the following concentration of 29.4% (metakaolin),

6.3% (40 wt% sodium hydroxide), 51.1% (sodium silicate solution), and 13.2% (water). Commercial tannin-rich bark water-soluble extract Colatan GT 10 (produced by Unitán in Argentina) (Haarla Ltd., Tampere, Finland), is obtained by means of physicochemical treatments on extracted substances of the Colorado Quebracho (*Schinopsis Lorenzii*), native to the Northeast region of Argentina. The tannin content of Colatan GT 10 was 116.8 mg/g**,** saccharide content of 1.2%, and average length of catechin units was 15, based on a preliminary acid-butanol assay. Colatan GT 10 was used as a Milli-Q water diluted solution.

The specimens were impregnated using the Bethell full-cell process, applying an initial vacuum of 15 kPa for 20 min at 20 °C, followed by an increase in pressure to 1000 kPa for 60 min at 20 °C. After the first impregnation, the specimens were dried at 50 °C until constant mass before the second impregnation. The chemical retention was calculated after each impregnation by comparing the oven-dried mass (at 50 °C) before and after impregnation to assess any increase in mass following the second impregnation compared to the first. However, only the final retention (kg/m^3) and the weight percentage gain (WPG) (%) were reported, as given by Eqs. 1 and 2.

$$\text{Weight percentage gain (WPG)}\,(\%) = \left[\left(M_1 - M_0\right)/M_0\right] \times 100 \quad (1)$$

where M_1 (g) is the dried mass after the second impregnation and M_0 (g) is the dried mass before the first impregnation.

$$\text{Chemical retention}\left(kg/\text{m}^3\right) = (M1 - M0)/V \quad (2)$$

where M_1 (kg) is the dried mass after the second impregnation and M_0 (kg) is the dried mass before the first impregnation, and V the volume of the sample (m^3).

2.3 Leaching test

Half of the specimens in each group were exposed to a leaching test following the European standard EN 84 (CEN 1997). The specimens were immersed in 1:5 (v/v) Milli-Q water for 14 days, with the water changed nine times during the process. An initial vacuum was applied corresponding to a pressure of 4 kPa, for 20 min. The first water changes took place after 24 and 48 h, followed by seven more changes within a 12-day period at intervals of 24 to 72 h. Subsequently, the leached specimens were oven-dried at 50 °C until consistent mass was observed. The dry mass before and after the leaching test were compared.

2.4 Decay test

The decay test was conducted following a modified version of the standard mini-block procedure in the European norm EN 113 (2021), as previously done by Barbero-López et al. (2022). The growth media was prepared by mixing 4% malt powder and 2% agar in Milli-Q water, which was then autoclaved at 120 °C for 15 min, and the pressure was increased by 10 kPa above atmospheric pressure. Later, 25 mL of liquid culture medium was poured into each Petri dish (Ø 90 mm, 15 mm height) under sterile conditions.

In this experiment, twenty replicates of each treatment (ten leached and ten non-leached) were exposed to each fungus. Three different brown-rot fungi were used: *Rhodonia placenta* (strain BAM 113), *Gloeophyllum trabeum* (strain BAM 115) and *Coniophora puteana* (strain BAM 112), purchased from the Federal Institute for Materials Research and Testing (BAM, Berlin, Germany). The inoculation was performed under sterile conditions with a plug (Ø 5.5 mm) of an actively growing fungus in the centre of each dish. The Petri dishes were sealed with parafilm and kept in a growth chamber at 22 ± 2 °C and 65 ± 5% relative humidity (RH).

Four wood specimens impregnated with the same chemical, i.e. two leached specimens and two non-leached specimens, were exposed to the fungus in each Petri dish as soon as the mycelium covered the entire surface of the culture medium, which occurred after approximately one to two weeks. All the wood specimens used for the experiment were autoclaved at 120 °C for 15 min under a pressure 10 kPa above atmospheric pressure. After sterilization, they were maintained in a laminar flow hood to ensure sterility before being exposed to fungi in Petri dishes. A plastic mesh inside the Petri dish was used to avoid direct contact between the wood and the growth media. The Petri dishes were sealed and kept in a growth chamber at 22 ± 2 °C and 65 ± 5% RH for 16 weeks. During harvesting, the specimens were cleaned from the mycelium. Subsequently, the dry mass of the wood specimens was measured at 50 °C and compared with their dry mass before exposure to decay, to determine the mass loss (wt-%) caused by the fungi.

To determine the mass loss, the dry specimens (50 °C) were weighed before and after decay exposure using Eq. 3.

$$\text{Mass loss}\,(\%) = \left[M_0 - M_1\right)/M_0] \times 100 \quad (3)$$

where M_1 (g) is the mass after decay exposure and M_0 (g) is the mass before decay exposure.

2.5 Infrared (IR) spectroscopy

The tannin, geopolymer and the interaction between them, in a mass ratio of 5:4, were investigated using a Fourier transform infrared (FTIR) spectrometer Vertex 70 (Bruker, Leipzig, Germany) equipped with an attenuated total reflectance (ATR), a sensitive 2 × 2 mm diamond crystal surface and a sample detector RT-DLaTGS. The same ATR-FTIR parameters recorded within the 4000–400 cm^{-1} range with

16 scans at a resolution of 2 cm^{-1} were used in the OPUS 6.5 software (Bruker, Leipzig, Germany) throughout the measurements.

2.6 Mechanical test

The modulus of elasticity (MOE) and the modulus of rupture (MOR) were determined using a three-point bending test conducted on a Zwick Roell Material Testing Machine Z050. Prior to testing, the specimens were conditioned at a 65 ± 5% RH and 20 ± 2 °C temperature until they reached a constant mass. Twenty replicates of each treatment (ten leached and ten non-leached), with dimensions of 40 × 10 × 5 mm, were utilized to calculate the MOE and MOR at a testing speed of 5 mm/min. The Eqs. 4 and 5 were used for calculating the MOE and MOR were as follows:

$$MOE(GPa) = \frac{L^3}{4bd^3}\frac{\Delta P}{\Delta y} \quad (4)$$

$$MOR(MPa) = \frac{3PL}{2bd^2} \quad (5)$$

where L is the distance between supports for the beam, with a value of 35 mm, P is the maximum load (N), b is the specimen width (mm), d is the specimen thickness (mm) and $\Delta P/\Delta y$ is the slope of the straight-line portion of the load–deflection curve (N/mm).

2.7 Statistical analysis

Statistical analysis was performed using the R statistical software. For each of the evaluated properties, the mean and standard error were calculated. Subsequently, an analysis of variance (ANOVA) was performed. Tukey's range test was used as a post-hoc for the ANOVA to compare the different treatments.

3 Results and discussion

3.1 Leaching test

The changes in the appearance of Scots pine sapwood following the different treatments are shown in Fig. 1. After the leaching test, the wood treated with 5% and 10% tannin showed a noticeable lightening in colour, indicating a significant loss of tannins. In contrast, the specimens subjected to combination treatments retained an appearance similar to that of the non-leached specimens.

The retention values after treatment and mass loss due to leaching (Table 1) show that the tannin-rich extract Colatan GT10 at 10% had the highest retention rate after impregnation and the highest mass loss after the leaching test. The specimens treated with 5% of tannin together with 2 and 4% of geopolymer had higher retention rates than those with tannin at 5% treatment, demonstrating a lower leachability of tannins during the second step

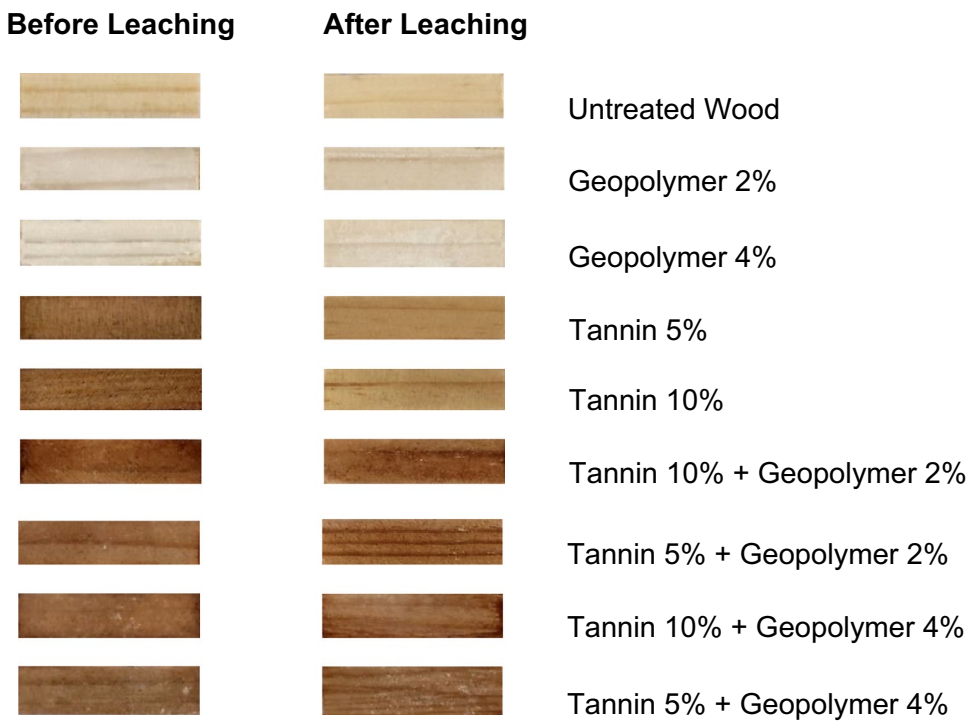

Fig. 1 Treatment comparison between leached and non-leached specimens

Table 1 Treatment abbreviations, weight percent gain (WPG), chemical and geopolymer retention values (after impregnation), and mass loss due to leaching

Treatment	Treatment abbreviation	WPG (%)	Chemical and geopolymer retention (kg/m^3)	Mass loss due to leaching (%)
Control	Ctrl	–	–	2.31 ± 0.08
Colatan GT10 5%	T5	10.26 ± 0.33	33.48 ± 1.08	8.97 ± 0.42
Colatan GT10 10%	T10	19.86 ± 0.60	66.08 ± 1.98	15.02 ± 0.59
Geopolymer 2%	G2	3.01 ± 0.88	7.86 ± 0.41	3.91 ± 0.09
Geopolymer 4%	G4	6.56 ± 0.21	17.90 ± 0.74	5.51 ± 0.39
Colatan GT10 5% + geopolymer 2%	T5G2	12.03 ± 0.28	37.28 ± 0.70	7.94 ± 0.43
Colatan GT10 5% + geopolymer 4%	T5G4	14.19 ± 0.78	45.55 ± 2.67	8.21 ± 0.27
Colatan GT10 10% + geopolymer 2%	T10G2	16.28 ± 0.51	54.07 ± 1.64	9.66 ± 0.47
Colatan GT10 10% + geopolymer 4%	T10G4	18.70 ± 0.19	60.60 ± 4.10	8.75 ± 0.55

Values are presented as mean ± standard error (% or kg/m^3)

of geopolymer treatment. Nonetheless, the specimens with 10% of tannin together with 2 and 4% of geopolymer treatments exhibited lower retention rates than those with tannin at 10% treatment, indicating that a portion of the tannins leached out after geopolymer impregnation. The mass loss due to leaching in all combination treatments (T5G2, T5G4, T10G2, and T10G4) was lower than their retention rates. Additionally, it is worth noting that the chemical residue remaining after the leaching test in all combined treatments was higher than in the plain tannin treatments, indicating an improvement in fixation when geopolymer is added. Plain geopolymer showed the lowest retention values among all the treatments. Among all the treatments, the plain geopolymer exhibited the least retention values. While the reason for this result is not entirely clear, we suspect that the particle size of the geopolymers may be a significant contributing factor. The particle size of metakaolin can range from 1 to 2 µm (Jamal et al. 2018). In addition, a previous study Song et al. (2018) reported that based on the particle size distribution, 90% of metakaolin particles are below 5.43 µm, with an average particle size of 1.73 µm. Another research Bossert et al. (2020) showed that impregnation limitations existed before the assumed particle size thresholds of 400–600 nm in pine and beech wood. The G2 treatment exhibited a slightly higher mass loss after leaching compared to retention. This discrepancy could be attributed to variations in the measurement techniques, such as precision errors during weighing or incomplete removal of water prior to post-leaching measurements.

In the context of two-step treatment, it is important to emphasize the potential benefits of incorporating tannins directly into the chemical formulation of geopolymers, thereby negating the necessity for an additional treatment step.

3.2 IR spectroscopy

The tannin, geopolymer, and tannin-geopolymer mixture were characterized using ATR FTIR (Fig. 2). The mixture was prepared by combining tannin and geopolymer in a mass ratio of 5:4.

The tannin spectrum exhibits significant peaks in the 1500–1600 cm^{-1} range, corresponding to C=C stretching vibrations from the aromatic rings (Ahmad et al. 2013). There are also notable peaks between 1000 and 1300 cm^{-1}, which correspond to C–O stretching, particularly associated with phenolic and ether groups. Additionally, peaks observed between 400 and 600 cm^{-1} are attributed to out-of-plane deformations of the aromatic rings or C–C bending vibrations within the rings (Ricci et al. 2015).

The geopolymer spectrum displays significant peaks around 900–1200 cm^{-1}, corresponding to the asymmetric stretching of Si–O–Si or Si–O–Al linkages (Zhang et al.2012; Deshmukh et al. 2013). Other peaks between 400 and 600 cm^{-1} are related to Si–O or Al-O bending vibrations (Rożek et al. 2018).

In the FTIR spectrum of the tannin-geopolymer mixture, the region between 900 and 1200 cm^{-1} shows slight changes in intensity. This suggests an interaction between the hydroxyl or phenolic groups of the tannin and the Si–O–Al network of the geopolymer, likely through hydrogen bonding. Moreover, the phenolic groups in the tannin may coordinate with Si species in the geopolymer, potentially altering the Si–O–Si or Si–O–Al bending vibrations observed in the 450–600 cm^{-1} region.

These findings suggest that tannins interact with the geopolymer matrix, potentially modifying the geopolymer's structural features, which could influence the material's properties.

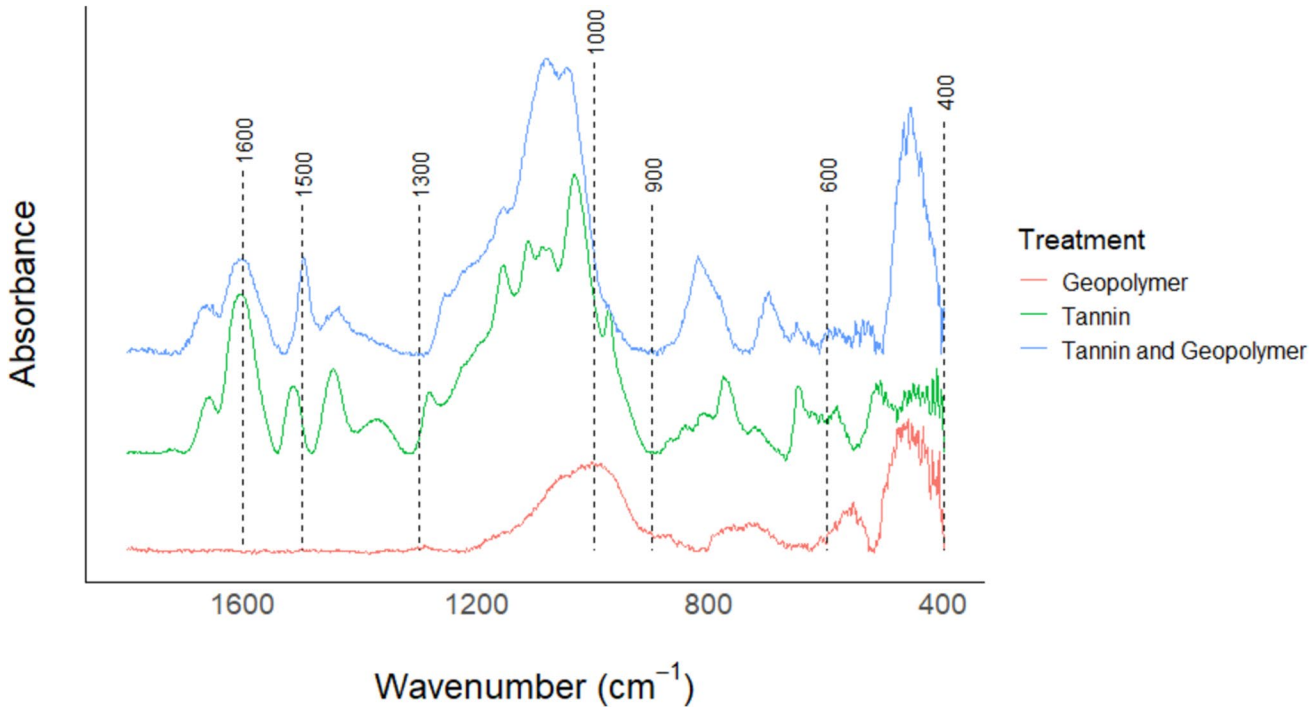

Fig. 2 ATR IR spectra of the geopolymer, tannin, and tannin with geopolymer in a mass ratio of 5:4

3.3 Wood decay test

The decay test results (Table 2) indicate a notably high overall mass loss. The wet mass of the specimens was recorded, showing approximately 45% moisture content relative to their dry mass (dried at 50 °C) after the decay test. This indicates that the humidity conditions during testing were sufficient to support a degradation environment. The combination treatments significantly increased the decay resistance of wood against *R. placenta*, *G. trabeum* and *C. puteana*. The wood specimens with T5 and T10 treatments without leaching had higher resistance than the untreated wood against all three fungi. This finding is consistent with previous studies that showed the antifungal properties of tannins against wood-degrading fungi (Anttila et al. 2013). However, there was no significant difference between the control and the T5 and T10 treatments after the leaching test.

The plain geopolymer treatments at 2% and 4% performed differently among the tested fungi. The non-leached geopolymer-treated wood at 2% and 4% exposed to *G.*

Table 2 Mass loss due to fungal decay exposure

	Mass loss (%)					
	Rhodonia placenta		Gloeophyllum trabeum		Coniophora puteana	
Treatment	Leached	Non-leached	Leached	Non-leached	Leached	Non-leached
Ctrl	29.9 ± 4.0^{a}	31.7 ± 4.5^{a}	17.8 ± 3.8^{a}	17.0 ± 3.8^{a}	26.4 ± 5.5^{a}	16.6 ± 4.1^{a}
T5	40.8 ± 4.1^{a}	11.3 ± 4.1^{bc}	19.2 ± 2.7^{a}	5.0 ± 0.4^{b}	33.1 ± 4.3^{a}	4.3 ± 0.3^{b}
T10	34.6 ± 4.3^{a}	3.6 ± 1.1^{c}	18.3 ± 4.6^{a}	5.6 ± 0.5^{b}	21.7 ± 4.1^{a}	5.9 ± 0.4^{b}
G2	27.7 ± 3.4^{a}	17.3 ± 3.6^{abc}	26.7 ± 6.5^{b}	3.1 ± 1.3^{b}	30,8 ± 4.1^{a}	15.0 ± 1.9^{a}
G4	30.7 ± 3.2^{a}	23.4 ± 4.7^{ab}	26.4 ± 6.8^{b}	2.9 ± 0.4^{b}	24.7 ± 4.0^{a}	6.9 ± 1.3^{b}
T5G2	19.5 ± 3.7^{ab}	11.6 ± 4.4^{bc}	15.0 ± 5.0^{ac}	2.2 ± 0.1^{b}	13.5 ± 3.1^{ab}	2.8 ± 0.5^{b}
T5G4	11.0 ± 3.7^{b}	8.5 ± 2.3^{c}	**9.5 ± 2.7^{c}**	3.5 ± 1.3^{b}	**9.4 ± 2.9^{b}**	3.8 ± 0.4^{b}
T10G2	13.1 ± 2.6^{b}	6.8 ± 3.1^{c}	**9.0 ± 3.3^{c}**	4.0 ± 0.4^{b}	14.2 ± 3.2^{ab}	3.3 ± 0.4^{b}
T10G4	11.4 ± 3.6^{b}	3.9 ± 1.6^{c}	11.1 ± 1.2^{c}	3.2 ± 0.7^{b}	**9.3 ± 2.9^{b}**	4.9 ± 0.6^{b}

Values are presented as mean ± std. error (%). Different letters indicate significant differences between treatments based on Tukey's range test. The results highlighted in bold represent mass loss values attributable to decay, remaining below 10% after the leaching test

trabeum improved the decay resistance at the same level of T5 and T10, contrary to the specimens exposed to *R. placenta*, wherein the G2 and G4 treatments did not differ from the untreated wood. On the other hand, when exposed to *C. puteana*, the G2 treatment did not exhibit a significant difference from the untreated wood, while the G4 treatment showed a significant reduction of mass loss compared with the untreated wood. The performance of the geopolymer-treated wood at 2% and 4% after leaching was similar against the three wood decay fungi, with no significant differences compared with the untreated specimens. These results are of special interest, considering that no previous works have been identified in the literature that tested the decay performance of wood treated with geopolymers.The combination treatments showed different results between the leached and non-leached specimens when exposed to the three fungi. Among all the combination treatments, the leached and non-leached specimens with T5G2 treatment had the highest mass loss caused by *R. placenta*. When the specimens with T5G2 treatment were exposed to *G. trabeum* and *C. puteana*, the non-leached specimens had a lower mass loss compared to the untreated wood specimens, while the leached specimens did not exhibit any significant difference from the untreated wood, indicating that the impregnation with geopolymer at 2% allowed the tannins at 5% concentration to leach.

All the remaining combination treatments (T5G4, T10G2 and T10G4) showed a significant reduction in mass loss compared to the control specimens when exposed to the three fungi, except for the leached specimens of T10G2 treatment exposed to *C. puteana*. After the leaching test, the T5G4, T10G2 and T10G4 treatments displayed a significant reduction in mass loss compared with the plain treatments (T5, T10, G2 and G4)**,** indicating the fixation of tannins into the wood. The mechanism behind this could be mechanical interlocking (Ye et al. 2021), chemical bonding, possibly via ether linkages, which can be influenced by several factors, such as the curing conditions (Shalbafan et al. 2016), or, as geopolymer is alkaline, it is likely to influence the auto-condensation of tannins (Merlin et al. 1996), leading to a more complex and stable chemical structure. The enhanced stability of these auto-condensed tannins typically results in a reduction tendency for them to leach out from wood. However, if tannin molecules undergo premature auto-condensation prior to penetrating the wood matrix, they may form larger macromolecular aggregates. These aggregates can make it difficult for the effective infiltration into the wood's cellular structure, limiting their ability to uniformly distribute within the pores and interact with the wood's chemical components. The T5G4, T10G2 and T10G4 treatments that were not exposed to leaching did not show any significant difference compared with the plain treatments (T5, T10, G2 and G4) in any of the three decay fungi, except for the G2 treatment exposed to *C. puteana*. Previous research, using the same methodology, has shown that the mass loss of copper-based treatment against C. puteana was $0.3 \pm 0.4\%$ for the leached specimens and $0.1 \pm 0.2\%$ for the non-leached specimens (Barbero-López et al. 2021). Other studies in wood preservation have shown the mass loss of alkaline copper quaternary (ACQ) ($3.09 \pm 1.76\%$), micronized ACQ ($27.20 \pm 6.09\%$), Nano CuO ($19.27 \pm 3.10\%$), and CCA ($4.10 \pm 0.99\%$) treatments against R. placenta, as well as ACQ ($12.99 \pm 1.98\%$), micronized ACQ ($4.23 \pm 0.45\%$), Nano CuO ($20.21 \pm 3.98\%$), and CCA ($3.21 \pm 2.90\%$) treatments against G. trabeum (Nami Kartal et al. 2015). Even though some of the combination treatments had a low value for mass loss due to decay, they are not as effective as the commercial one. However, the performance is subject to the concentration of the preservatives. Ma et al. (2013) showed the decay resistance of alkaline copper quaternary (ACQ-C) and copper azole (CA-C) treatments with different concentrations against *G. trabeum* and *Trametes versicolor*, obtaining significant variation depending on the concentration. Additionally, the copper-based preservative-treated wood must undergo a decontamination process for disposal (Janin et al. 2011).

3.4 Mechanical test

The results of the three-point bending test (Table 3) revealed a small variance among the treatments concerning the MOE and MOR, which can be attributed to multiple factors, including treatment process and the interaction between them. In the case of MOE, the non-leached specimens treated with T10 exhibited a significantly higher value than the control, while other treatments showed no significant differences compared to the control. This finding suggests that T10 treatment may enhance MOE, especially in low-density wood species as previously reported by Cesprini

Table 3 MOR and MOE of the leached and non-leached specimens

Treatment	MOE (GPa)		MOR (MPa)	
	Non-leached	Leached	Non-leached	Leached
Ctrl	2.0 ± 0.2^{a}	1.8 ± 0.1^{a}	54.9 ± 3.1^{a}	46.9 ± 2.1^{ab}
T5	2.4 ± 0.2^{ab}	2.5 ± 0.2^{bc}	53.1 ± 3.0^{a}	53.8 ± 2.8^{ab}
T10	2.6 ± 0.1^{b}	2.7 ± 0.1^{c}	53.9 ± 2.0^{a}	57.4 ± 2.1^{a}
G2	2.0 ± 0.1^{a}	1.9 ± 0.2^{a}	43.2 ± 1.7^{b}	43.5 ± 2.9^{b}
G4	2.1 ± 0.1^{a}	2.2 ± 0.1^{ab}	46.7 ± 2.8^{ab}	47.9 ± 2.5^{ab}
T5G2	2.2 ± 0.1^{a}	2.1 ± 0.1^{abc}	49.7 ± 2.4^{a}	51.9 ± 2.6^{ab}
T5G4	2.2 ± 0.1^{a}	1.9 ± 0.1^{ab}	50.1 ± 2.0^{a}	47.7 ± 2.9^{ab}
T10G2	2.1 ± 0.2^{a}	1.9 ± 0.2^{ab}	48.4 ± 2.7^{a}	49.2 ± 2.3^{ab}
T10G4	2.3 ± 0.2^{ab}	2.2 ± 0.1^{abc}	52.9 ± 3.9^{a}	49.5 ± 2.6^{ab}

Values are presented as mean ± std. error. Different letters indicate significant differences between treatments based on Tukey's range test

et al. (2022). This effect may be attributed to tannins' ability to strength the cell wall and reduce the formation of cracks under mechanical stress by filling gaps within the wall components, thereby reducing crack initiation or propagation. Additionally, although the T5 treatment did not show a statistically significant difference compared to the control, its slightly higher value indicates that tannin concentration could influence MOE performance. After the leaching test, the MOE values for T5 and T10 treatments displayed the highest values, showing a significant difference from both the control and the G2 treatment. This demonstrates that these treatments provide improved resistance to leaching conditions, which is not entirely consistent with the leaching results. One possible explanation is that, although tannins are the primary agents responsible for the improved MOE, their leaching does not necessarily reverse all the changes they caused. Structural alterations or residual tannins might still maintain a stiffness level higher than that of untreated wood. The treatments G4, T5G2, T5G4, T10G2, and T10G4 did not exhibit any significant difference compared to the control specimens, possibly due to the treatment process.

For the MOR, the non-leached specimens treated with G2 displayed the lowest value, which was significantly different from the other treatments except for the G4 treatment. This reduction in MOR can be attributed to the low retention, low concentration, and the particle size of metakaolin (Song et al. 2018; Carmo-Gonçalves et al. 2022). Earlier studies have shown that geopolymer concrete exhibits a lower MOE than conventional concrete, with values ranging from 10 to 30 GPa (Sofi et al. 2007; Fernández-Jiménez et al. 2003; Nath et al. 2017). This difference is attributed to the amorphous nature of the geopolymer (Murali et al. 2024). Despite this, the MOR of geopolymer concrete can surpass that of conventional concrete, reaching values ranging from 5 to 15 MPa. This is attributed to the dense microstructure and good bonding between the geopolymer binder and aggregates (Murali et al. 2024). The incorporation of reinforcing fibers, such as carbon fibers, has also been shown to enhance both MOE and MOR (Mamatha et al. 2023).

Interestingly, the MOR values of all tested treatments remained stable after the leaching test, with the exception of the control specimens, where MOR was reduced. This indicates that the treatments reduced the leaching-induced degradation, preserving their structural integrity. The reduction in MOR for the control specimens highlights the susceptibility of untreated materials to environmental exposure.

4 Conclusion

The use of geopolymers as a component in treatment formulations to enhance the biodegradation resistance of wood after leaching exposure has demonstrated significant benefits. Specifically, the combined treatment of 5% tannin and 4% geopolymer effectively improved decay resistance after leaching, showing the lowest mass loss values (11.0%, 9.5%, and 9.4%) against different fungal species. Additionally, the treatment combination of 5% tannin and 2% geopolymer did not compromise the mechanical properties of the wood after the leaching test, while also exhibiting the lowest mass loss due to leaching among all tested combination treatments.

Future research should focus on evaluating the homogeneity of the treatment, as well as its wear and fire resistance, and the depth of penetration into the wood. Furthermore, investigating different concentrations and exploring the feasibility of a one-step treatment process could optimize the method, making it more suitable for large-scale application.

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Data availability The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors declare no competing interests.

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