

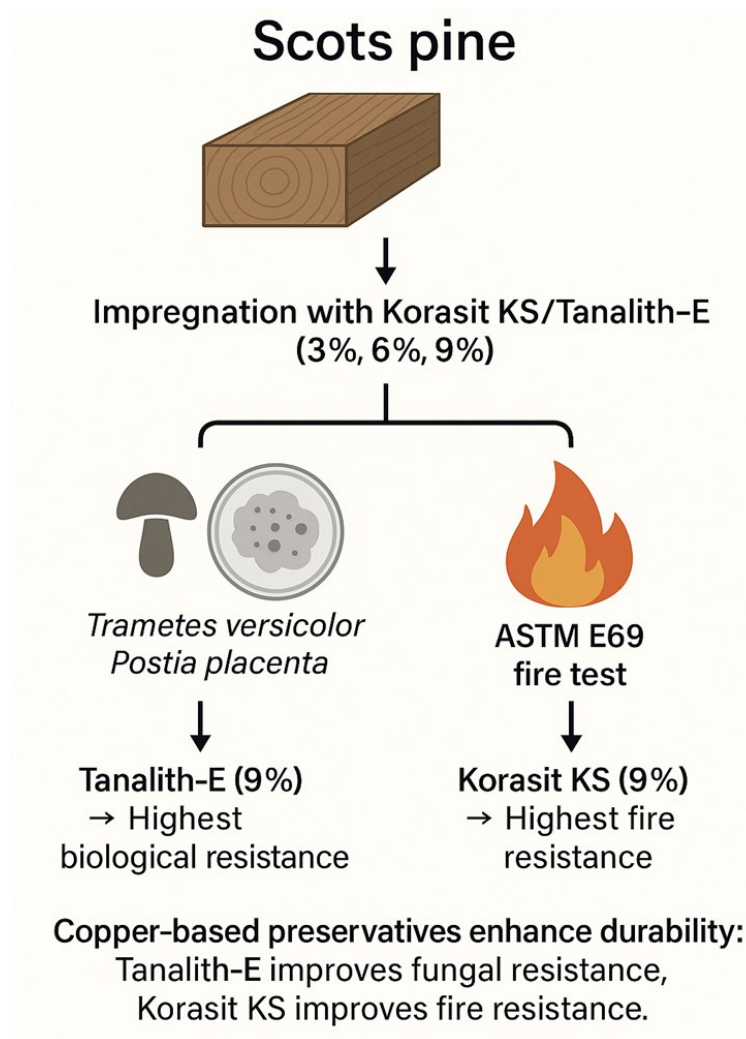
Evaluation of Biological and Fire Resistance of Scots Pine Wood Impregnated with Commercial Copper-based Preservatives

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DOI: 10.15376/biores.20.4.9804-9816

GRAPHICAL ABSTRACT



Evaluation of Biological and Fire Resistance of Scots Pine Wood Impregnated with Commercial Copper-based Preservatives

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The objective of this work was to enhance fire and decay resistance of wood materials using environmentally friendly and non-toxic wood preservatives. Two copper-based impregnation agents, Korasit KS and Tanalith-E, were applied to Scots pine (*Pinus sylvestris* L.) specimens. The fire performance was evaluated with ASTM E69 (2002) by measuring mass loss after fire exposure. Decay resistance was assessed according to EN 113 (2006), using white-rot fungus *Trametes versicolor* and brown-rot fungus *Postia placenta* over a 12-week incubation period. Specimens treated with 9% concentration of Korasit KS exhibited the lowest mass loss after fire exposure. Similarly, increasing the concentrations of both preservatives resulted in reduced mass loss under fire conditions. Data were statistically analyzed using one-way ANOVA and Duncan's test ($\alpha = 0.05$). Specimens impregnated with 9% Tanalith-E showed the lowest mass loss and the highest resistance to both *T. versicolor* and *P. placenta*. Overall, it is recommended that wood materials intended for industrial applications be impregnated with higher concentrations of Korasit KS to improve fire resistance, and with Tanalith-E to enhance biological durability against fungal decay.

DOI: 10.15376/biores.20.4.9804-9816

Keywords: Korasit KS; Tanalith-E; *Trametes versicolor*; *Postia placenta*; Scots pine; *Pinus sylvestris* L.; Fire resistance; Decay resistance; Copper-based wood preservatives

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INTRODUCTION

Wood is one of the most abundant natural materials and possesses several advantages compared to other construction materials. It is a renewable material characterized by low density, low thermal conductivity, high mechanical strength, and ease of processing, along with an aesthetically pleasing appearance (Pandey 1999). However, wood is susceptible to degradation caused by both biotic and abiotic factors. Among abiotic factors, ultraviolet (UV) radiation is most significant, while decay caused by fungi constitutes the primary biotic threat. These factors lead to the deterioration of wood's favorable properties, significantly reducing its density, strength, and appearance. Particularly, fungal decay is one of the most critical problems, threatening the structural integrity of wood and shortening its service life (Öztürk and Perker 2024). Many wood species do not possess sufficient natural durability for outdoor applications without protective treatment. Therefore, wood materials used in exterior environments must be properly preserved (Feist and Hon 1984, Pelit *et al.* 2017; Korkmaz *et al.* 2024).

One of the most common preservation techniques is impregnation, which aims to extend the service life of wood by increasing its resistance to degrading agents. Untreated wood, especially when exposed to high moisture or in contact with soil, is vulnerable to fungal and bacterial attacks that result in discoloration, mold formation, and decay. These effects deteriorate the physical and technological properties of the material, leading to premature failure (Pelit and Korkmaz 2019). Copper-based wood preservatives have been widely used in the wood protection industry over the last 50 years due to their high efficacy against fungi. The ban on chromated copper arsenate (CCA), once dominant in the market, has led to the development of safer and environmentally friendly alternatives. Modern research focuses not only on the toxicity of these alternatives but also on their long-term leaching behavior and ecotoxicological profiles (Changotra *et al.* 2024). Common alternatives include Korasit KS, alkaline copper quaternary (ACQ), copper azole (CA and MCA), copper naphthenate, copper-HDO, acid copper chromate (ACC), and Tanalith-E. These compounds are known to enhance decay resistance with low toxicity to humans and animals (Humar *et al.* 2001).

Most wood preservatives that provide protection against fungal attack interfere with fungal metabolism by blocking acetyl-CoA synthesis or inhibiting respiratory enzymes (Eaton and Hale 1993; Zhang 1999). Copper-containing preservatives are believed to act through metal–enzyme interactions, free radical formation, and DNA modification (Zhang 1999). In recent years, natural compounds, such as enzymatically hydrolyzed okara, have been investigated to enhance the fixation of antifungal salts in wood (Ahn *et al.* 2010; Kim *et al.* 2011). Additionally, tannin-based systems have shown promising decay resistance when combined with copper or boron salts (Laks *et al.* 1998; Tondi *et al.* 2012).

Extensive academic research and industrial applications confirm that copper-based impregnation significantly improves resistance against fungal degradation (Sivrikaya and Can 2014). For instance, Zhang (2015) evaluated the performance of copper azole and water repellents against specific wood-decay fungi, further reinforcing their widespread use. In field studies, wood stakes treated with MCA demonstrated enhanced longevity, while untreated controls degraded rapidly. Recent experimental studies also support the multifunctional performance of copper-based and nano-modified preservative systems, reporting improvements in decay resistance, thermal stability, and durability under leaching or field-like conditions (Zhao *et al.* 2021; Khademibami *et al.* 2022). Recent studies with Korasit KS reported favorable changes in thermal and surface properties after treatment and weathering, supporting its practical relevance for exterior applications (Altay 2022).

Another major drawback of wood is its combustibility. Combustible materials can ignite spontaneously upon reaching a critical temperature, even without an external flame. While some treatments can slow the combustion process, complete fireproofing is not possible. Preservatives decompose below the degradation temperature of cellulose, forming char and water instead of flammable volatiles. This mechanism reduces the flammability of wood and slows down flame spread (Bozkurt *et al.* 1993). Although nanoparticles such as nano-silica have been studied in wood protection, their relevance in this work is mainly as co-additives to copper systems, which remain the primary preservatives investigated. Recent studies have focused on multifunctional preservatives, capable of simultaneously improving both decay and fire resistance. Incorporation of nanoparticles into copper-based systems, for example, has been shown to increase both fire

retardancy and biological durability (Chen and Gérardin 2024). However, the long-term interactions between multiple chemical components remain a critical research issue.

The comparative performance evaluation of widely used commercial preservatives, such as Korasit KS and Tanalith-E, which are designed to serve different purposes, is essential for guiding industrial applications. Fire resistance of wood can be enhanced by treating the material with chemical fire retardants (Le Van and Winandy 1990). These treatments are crucial for delaying flame spread during a fire event (Richardson 1978).

Inorganic-based fire retardants remain the most commonly used in commercial wood protection. These include ammonium sulfate, ammonium chloride, boron compounds, phosphoric acid, zinc chloride, chromium, and copper salts (Baysal 1994). Can *et al.* (2017) investigated the combustion behavior of fir wood treated with copper azole (Tanalith E-3492) and ammonium copper quaternary (ACQ) and found significantly lower weight loss in treated specimens. Similarly, Örs *et al.* (1999) found improved fire resistance in Scots pine and beech wood impregnated with copper sulfate, especially when applied using pressure methods.

In this context, this study aimed to evaluate the fire resistance and fungal decay resistance of Scots pine (*Pinus sylvestris* L.) specimens impregnated with two copper-based preservatives: Korasit KS and Tanalith-E. The ultimate goal was to identify the most effective formulation and concentration for improving wood durability and to support sustainability in industrial applications. Although many studies have reported the effects of copper-based preservatives on fungal resistance or fire retardancy, most of these investigations evaluated these aspects separately. Only limited research has simultaneously assessed the dual biological and fire performance of treated wood, and the comparative effects of commercial formulations remain poorly understood. In particular, little attention has been given to the differences between boron-containing (Korasit KS) and azole-containing (Tanalith-E) preservative systems under standardized conditions. This study is novel in that it directly compares the dual protective performance of Korasit KS and Tanalith-E in Scots pine, addressing a critical gap in the literature by jointly evaluating their decay and fire resistance. Hypothesis tested: Increasing the concentration of Korasit KS and Tanalith-E significantly improves (i) fungal decay resistance and (ii) fire resistance of Scots pine compared to untreated controls.

EXPERIMENTAL

Materials

Preparation of wood samples

In this study, Scots pine (*Pinus sylvestris* L.), a widely used softwood species in exterior applications across Türkiye, was selected as the test material. The specimens were obtained from first-grade lumber with straight grain, free from cracks, growth defects, discoloration, density variations, and biological degradation. Sapwood sections in the radial direction were chosen. According to the guidelines specified in TS ISO 3129 (2012), specimens were rough-cut to $22 \times 22 \times 22 \text{ mm}^3$ for decay resistance tests and $12 \times 22 \times 1020 \text{ mm}^3$ for fire tests.

The samples were conditioned at $20 \pm 2^\circ\text{C}$ and $65 \pm 3\%$ relative humidity (RH) in a climate chamber until they reached a constant mass (TS ISO 13061-1:2021). The pre-conditioned specimens were then planed and resized to their final dimensions, $19 \times 19 \times$

19 mm³, for fungal decay tests and 9 × 19 × 1016 mm³ for fire tests. This reduction from 22 mm to 19 mm was carried out to remove machining defects after pre-conditioning and to ensure precise fitting into the incubation chambers and fire test holders. All specimens were sanded and pre-soaked prior to impregnation.

Impregnation materials

Two copper-based commercial wood preservatives widely used in the timber industry were selected: Tanalith-E and Korasit KS.

- Tanalith-E is a new-generation copper azole-based preservative developed for protection against fungi and insects.
- Korasit KS is a dual-purpose preservative offering both biological protection and fire-retardant properties.

Both preservatives were applied at three concentration levels: 3%, 6%, and 9% by weight in aqueous solutions. The differing chemical compositions and functional characteristics of these products played a critical role in the interpretation of test results. The technical specifications and active ingredients of the preservatives used are summarized in Table 1.

Table 1. Technical Properties and Active Components of the Commercial Wood Preservatives Used in the Study

Property	Tanalith-E	Korasit KS
Manufacturer / Brand Owner	Arxada (formerly Lonza Wood Protection)	Kurt Obermeier GmbH & Co. KG (Korasit® brand)
Main Active Components	- Copper carbonate (14 to 18%) - Tebuconazole (azole group fungicide) (0.8 to 1.5%) - Quaternary ammonium compound (2 to 4%)	- Copper compounds (~10 to 15%) - Boric acid / Borax (15 to 20%) - Quaternary ammonium compound (2 to 5%)
Primary Function	Protection against biological agents such as fungi and insects	Dual-purpose: Protection against biological agents and enhanced fire resistance
Relevance to Study Findings	Exhibited superior biological resistance due to high copper-azole content	Provided significantly higher fire resistance than Tanalith-E by forming a char layer <i>via</i> boron compounds
Physical Form	Water-soluble concentrate	Water-soluble concentrate

Methods

Impregnation procedure

The impregnation process was carried out using the vacuum–pressure method, following the ASTM D1413 (2007) standard. All impregnation treatments were conducted at a solution temperature of 20 ± 2 °C, in accordance with standard practice for copper-based preservatives. For each treatment group, aqueous solutions of the preservatives were prepared at 3%, 6%, and 9% concentrations. Specimens were placed inside an impregnation cylinder and subjected to an initial vacuum of −0.08 MPa for 30 min to remove air from the wood’s cellular structure. Then, the preservative solution was introduced into the cylinder and a pressure of 1.2 MPa was applied for 60 min to ensure effective penetration. After pressure release, the specimens remained immersed under atmospheric conditions for 20 min to allow absorption of any remaining solution.

Following treatment, the specimens were reconditioned at 20 ± 2 °C and $65 \pm 3\%$ RH for 7 days in a ventilated chamber. The amount of retention (net solid uptake) in kg/m^3 was calculated using the following Eq. 1 ,

$$\text{Retention} = \frac{G \cdot C}{V} \times 10^3 \text{ (kg/m}^3\text{)} \quad (1)$$

where G is the weight gain ($T_2 - T_1$), T_1 is the initial weight of the specimen (kg), T_2 is the final weight after treatment (kg), V is the volume of the specimen (m^3), and C is the concentration of the treatment solution (%).

Decay test

Decay resistance tests were conducted in accordance with EN 113 (2006). The test fungi included *Trametes versicolor* (white-rot) and *Postia placenta* (brown-rot). Wood specimens with dimensions of $19 \times 19 \times 19 \text{ mm}^3$ were sterilized and placed into petri dishes containing malt-agar medium, then inoculated with the respective fungal strains.

The samples were incubated for 12 weeks in a controlled environment at 22 ± 2 °C temperature and $70 \pm 5\%$ relative humidity. After incubation, each specimen was oven-dried and weighed. The weight loss (%) caused by fungal degradation was calculated using the following Eq. 2,

$$\text{Weight loss (\%)} = \frac{T_1 - T_2}{T_1} \times 100 \quad (2)$$

where T_1 is the dry weight before incubation (g), and T_2 is the dry weight after incubation (g).

Fire test

The fire resistance of the treated and untreated wood specimens was evaluated according to the principles of ASTM E69 (2002). Test samples with dimensions of $19 \times 19 \times 19 \text{ mm}^3$ were first conditioned for six weeks at a temperature of 20 ± 2 °C and relative humidity of $65 \pm 3\%$ to achieve equilibrium moisture content.

The combustion test was conducted under a fume hood using a butane gas burner producing a steady flame with a height of 25 cm. During the test, each specimen was exposed to direct flame for 4 min, followed by an additional 6 min of glowing combustion without flame. The entire test duration was 10 min.

A precision digital balance continuously monitored and recorded the weight loss of each specimen in real time during the test. After exposure, the final weight loss (%) was calculated using the following Eq. 3,

$$\text{Weight Loss} = \frac{W_{bf} - W_{af}}{W_{bf}} \times 100 \quad (3)$$

where W_{bf} is the initial oven-dry weight before fire exposure (g), and W_{af} is the final oven-dry weight after fire exposure (g).

The experimental setup used for fire testing is illustrated in Fig. 1. In this setup, specimens were suspended with heat-resistant wire at a fixed distance of 30 mm above the gas burner. The flame height was adjusted to 20 mm according to ASTM E69, and combustion duration was monitored with a digital timer to ensure consistency across tests.

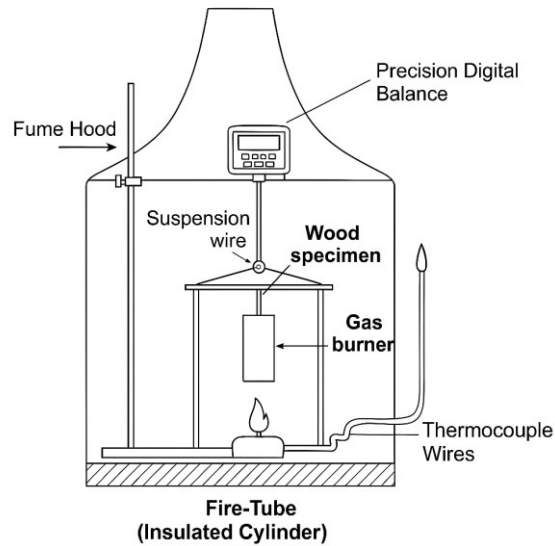


Fig. 1. The fire test setup

Statistical evaluation

The test results were statistically analyzed using the SPSS statistical software package. One-way analysis of variance (ANOVA) was performed to determine the significance of differences among the treatment groups. Where significant differences were found, Duncan's multiple range test was used for *post-hoc* comparisons. The results were evaluated at a 95% confidence level ($p < 0.05$). Each treatment group consisted of $n = 10$ specimens. Treatment groups were categorized into homogeneous subsets based on statistical similarity, and differences between groups were indicated using different letter notations. These letter groupings reflect statistically significant differences in the weight loss values caused by fungal and fire exposure.

RESULTS AND DISCUSSION

Anti-fungal Resistance

The weight loss values, standard deviations, and Duncan test results of Scots pine (*Pinus sylvestris* L.) specimens subjected to *Trametes versicolor* (white-rot) and *Postia placenta* (brown-rot) fungi are presented in Table 2.

Although weight loss in the control groups differed between the two fungal types, the difference was not statistically significant within each fungus. Among all groups, the highest weight loss was recorded in the untreated specimens exposed to *P. placenta*, while the lowest weight loss was observed in specimens treated with 9% Tanalith-E and exposed to *T. versicolor*.

In general, weight loss decreased as the concentration of both preservatives increased. Control samples were categorized in group "A" based on Duncan's homogeneity subsets, while specimens treated with 3% and 6% Korasit KS and exposed to *P. placenta* fell into group "B". In most cases, Tanalith-E treatments resulted in lower weight loss values compared to Korasit KS at the same concentration levels, indicating superior anti-fungal performance.

Table 2. Weight Loss of Impregnated Wood Specimens Exposed to White-rot and Brown-rot Fungi

Decay Fungus	Chemicals	Retention (%)	Retention Amounts (kg/m ³)	Weight Loss (%)	Standard Deviation	Homogeneity Group	Coefficient of Variation
White-rot fungus (<i>Trametes versicolor</i>)	Control	-	-	28.45	1.50	A	4.52
	Corasit KS	3	16.45	12.25	3.07	BC	25.06
		6	18.74	10.59	6.79	BC	64.11
		9	19.13	8.15	3.45	C	42.33
	Tanalith-E	3	15.23	9.88	7.88	C	79.75
		6	17.88	7.12	3.13	CD	43.96
		9	19.13	6.36	4.17	CD	65.56
Brown-rot fungus (<i>Postia placenta</i>)	Control	-	-	34.14	6.79	A	23.63
	Corasit KS	3	15.13	15.19	13.45	B	88.54
		6	16.99	13.49	6.36	B	47.14
		9	17.12	11.12	3.13	BC	28.14
	Tanalith-E	3	15.45	12.05	5.48	BC	45.47
		6	19.88	10.87	6.79	BC	62.46
		9	20.12	8.95	1.12	C	12.51

Note: Each group received ten replicas. At a 95% confidence level, homogeneity group was attained

These findings align with previous research. For example, Tomak *et al.* (2021) investigated the resistance of Scots pine to *T. versicolor* and *Coniophora puteana* using zinc chloride (ZnCl₂), nano-ceria (CeO₂), nano-zinc oxide (ZnO), and copper sulfate (CuSO₄). They found that copper-containing preservatives significantly reduced fungal weight loss, especially at concentrations of 1.5% and above. The current study's results with copper-based preservatives support this outcome.

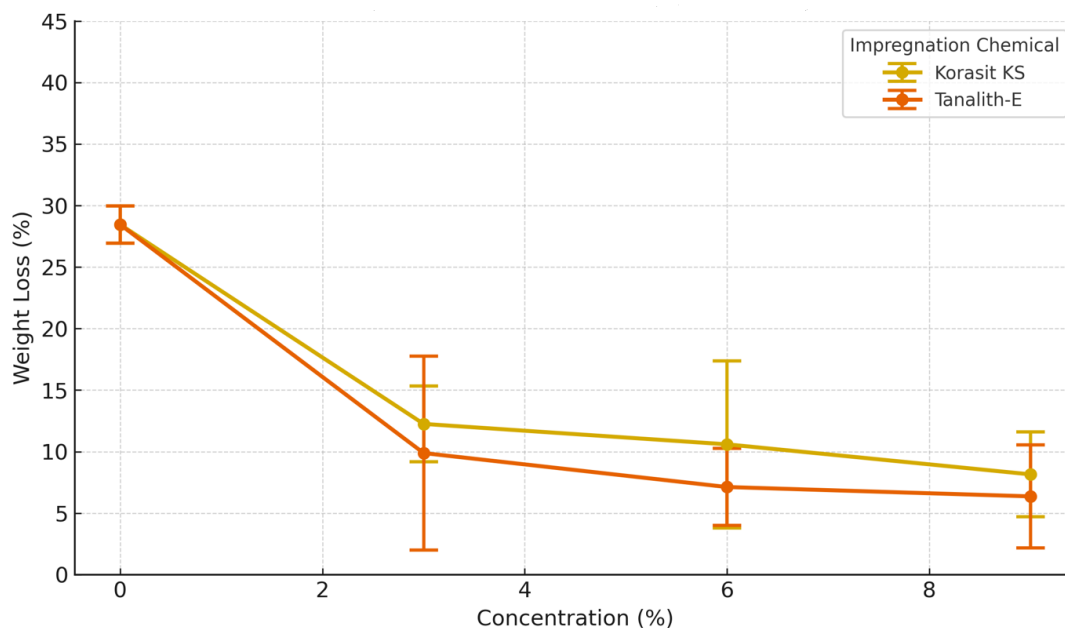


Fig. 2. Average weight loss (%) of Scots pine after exposure to *Trametes versicolor*. Error bars indicate ± 1 standard deviation ($n = 10$).

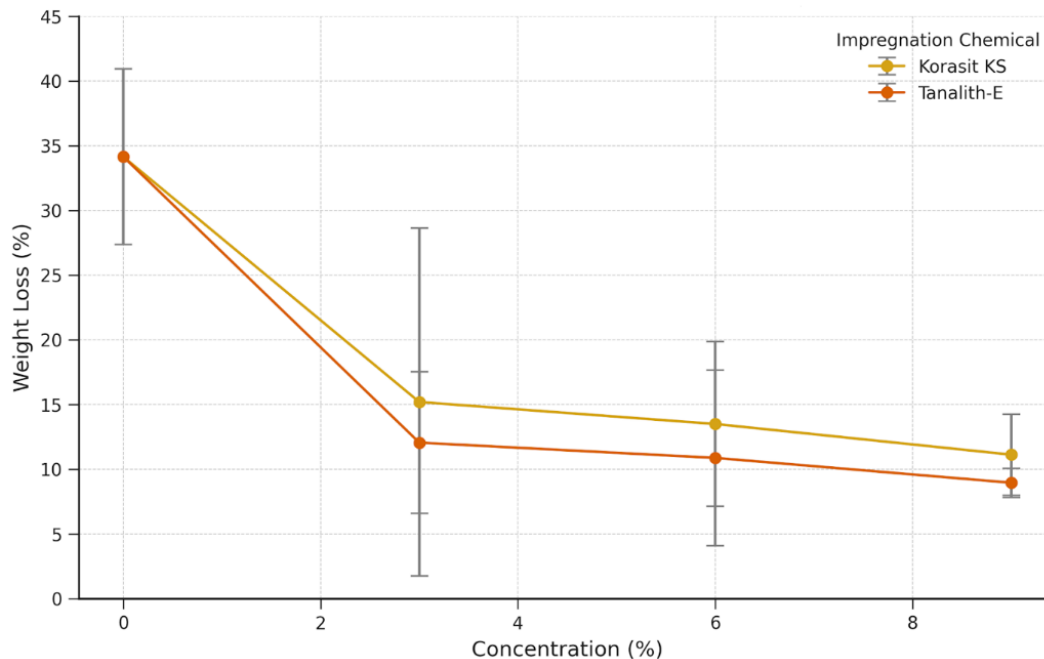


Fig. 3. Average weight loss (%) of Scots pine (*Pinus sylvestris* L.) after exposure to *Postia placenta*, according to impregnation chemical and concentration levels. Error bars indicate ± 1 standard deviation ($n = 10$).

Similarly, Terzi *et al.* (2016) reported that only nano-CuO and nano-SnO₂ were effective against *T. versicolor*, while other nanoparticles, such as ZnO and CeO₂, offered moderate protection. In another study by Temiz *et al.* (2014), Scots pine specimens treated with copper azole (Tanalith E3491) showed minimal weight loss when exposed to *P. placenta*, whereas untreated controls experienced over 40% degradation.

In addition to statistical significance, effect sizes were also reported in the present study. For fungal decay resistance, preservative type ($\eta^2 = 0.41$) and concentration ($\eta^2 = 0.46$) accounted for a substantial portion of the variance. For fire resistance, preservative type ($\eta^2 = 0.38$) and concentration ($\eta^2 = 0.44$) likewise indicated strong practical effects. These results demonstrate that the observed differences are not only statistically significant but also meaningful in magnitude.

As illustrated in Figs. 2 and 3, weight loss decreased consistently with increasing preservative concentration. This trend was especially evident in the Tanalith-E treatment groups.

Fire Resistance

The weight loss values of Scots pine (*Pinus sylvestris* L.) specimens treated with copper-based wood preservatives after fire exposure are presented in Table 3.

The highest weight loss after fire exposure was observed in the control group, with a value of 87.0%. The results showed that as retention levels increased, the weight loss values of the specimens decreased. Among all treatment groups, specimens impregnated with 9% Korasit KS exhibited the lowest weight loss (72.1%) and thus provided the most effective fire-retardant performance.

Table 3. Weight Loss of Copper-treated *Pinus sylvestris* L. Specimens after Fire Exposure at Different Retention Levels and Preservative Concentrations

Chemicals	Retention (%)	Retention Amounts (kg/m ³)	Weight Loss (%)	Standard Deviation	Homogeneity Group	Coefficient of Variation
Control	-	-	86.96	1.50	A	1.72
Korasit KS	3	15.13	80.13	3.07	AB	3.83
	6	16.44	76.66	6.79	B	8.85
	9	18.13	72.12	4.85	C	6.72
Tanalith-E	3	15.77	84.14	2.36	A	2.80
	6	17.12	83.42	6.78	A	8.12
	9	17.46	79.45	8.12	AB	11.22

Note: Each group received ten replicas; at a 95% confidence level, homogeneity group was attained

Keskin *et al.* (2013) investigated the fire properties of rowan wood (*Sorbus aucuparia* L.) impregnated with Tanalith-E, a copper-based preservative. They reported that the weight loss of the control group was 84.7%, while that of the Tanalith-E-treated samples reached 86% after fire testing. However, the difference between the control and the Tanalith-E-treated specimens was not statistically significant in terms of weight loss. Many wood preservatives contain copper as an active ingredient due to its high efficacy against fungal decay (Mourant *et al.* 2008). Moreover, copper-based aqueous solutions are relatively easy to prepare and analyze for penetration into wood (Archer and Preston 2006).

In another study, Can *et al.* (2017) treated fir wood (*Abies nordmanniana* subsp. *bornmuelleriana*) with copper azole (Tanalith E-3492) and ammonium copper quaternary (ACQ). Their results showed that the treated specimens had lower weight loss values than the untreated controls. The findings of the current study are largely consistent with those reported by Keskin *et al.* (2013) and Can *et al.* (2017).

The superior fire resistance exhibited by Korasit KS compared to Tanalith-E in the current study (with a weight loss value of 72.1%) is directly related to the chemical composition of the preservative. Korasit KS is presumed to contain phosphorus and/or boron compounds, which act as catalysts that promote cellulose dehydration during pyrolysis. This process leads to the formation of a stable char layer instead of flammable gases. However, this explanation is based on literature-supported hypotheses rather than direct chemical analysis in the present study and should therefore be regarded as a limitation. Future studies should include chemical characterization to confirm this proposed mechanism. Recent advanced thermal analysis studies confirm that such flame-retardant additives create an insulating char layer, reducing heat transfer and limiting the release of volatile gases (Zhang *et al.* 2025). This protective char barrier slows down the transfer of heat between the flame and the unburned inner wood, thereby reducing combustion intensity and overall degradation.

In the current study, increasing the preservative concentration resulted in a significant reduction in post-fire weight loss, particularly in specimens treated with Korasit KS. Additionally, the control, 3% Tanalith-E, and 6% Tanalith-E groups belonged to the same homogeneity group (A), indicating no statistically significant difference among them. However, specimens treated with 3% Korasit KS and 9% Tanalith-E were classified into the AB group, demonstrating intermediate fire resistance. As shown in Fig. 4, the increase

in preservative concentration—especially in Korasit KS—led to a marked improvement in fire resistance, as evidenced by reduced weight loss values after fire exposure.

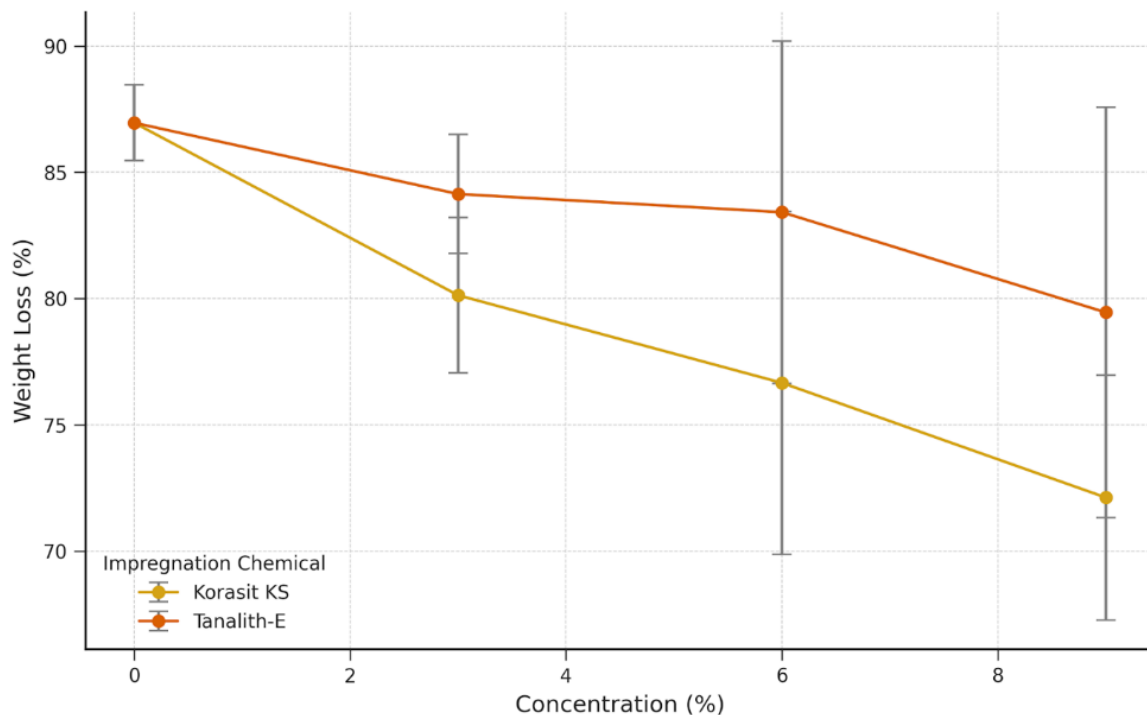


Fig. 4. Average weight loss (%) of Scots pine (*Pinus sylvestris* L.) after fire exposure, according to impregnation chemical and concentration levels. Error bars indicate ± 1 standard deviation ($n = 10$).

Recommendations

Based on the experimental findings, the following recommendations can be made:

- For applications where fire resistance is critical, Korasit KS at high concentrations is recommended. However, it should be noted that fire-retardant treatments may have adverse effects on the mechanical properties of wood. A recent study reported that some high-concentration fire-retardant salts can reduce the modulus of elasticity and modulus of rupture of wood materials. Therefore, in structural applications where mechanical performance is essential, the trade-off between fire resistance and strength must be carefully considered. Given its superior fungal resistance, Tanalith-E may be a more appropriate choice in load-bearing elements.
- For structures requiring protection against biological degradation (especially those in contact with soil or exposed to exterior weathering), Tanalith-E at higher concentrations is highly recommended.
- A concentration level of 9% is generally suggested, as it yielded the best overall results in both decay and fire resistance tests.
- Low-concentration impregnation treatments were found to be inadequate for long-term protection and may significantly reduce the economic lifespan of the wood material.

CONCLUSIONS

In this study, the biological durability and fire resistance of Scots pine (*Pinus sylvestris* L.) specimens impregnated with two copper-based wood preservatives—Korasit KS and Tanalith-E—were evaluated against common wood-degrading organisms, including the white-rot fungus (*Trametes versicolor*) and the brown-rot fungus (*Postia placenta*), as well as under fire exposure.

According to the results:

1. In the decay tests, the highest weight loss was observed in the control groups, with values of 28.4% and 34.1% for *T. versicolor* and *P. placenta*, respectively. Specimens treated with 9% Tanalith-E exhibited the lowest weight loss for both fungi (6.4% and 9.0%, respectively). In general, higher preservative concentrations led to increased resistance to fungal degradation. Overall, Tanalith-E was found to be more effective than Korasit KS in terms of biological durability.
2. In the fire tests, the control group showed the highest weight loss (87.0%), while the specimens treated with 9% Korasit KS had the lowest value (72.1%). An increase in preservative concentration improved fire resistance, and Korasit KS demonstrated better fire-retardant performance compared to Tanalith-E.
3. This study has certain limitations, as tests were performed only under laboratory conditions, with a single wood species, and without long-term outdoor exposure. Therefore, the results may not fully reflect in-service performance. Future studies should investigate the effects of preservative treatments on mechanical properties, evaluate additional wood species, and include natural weathering or field tests to confirm long-term durability and fire resistance.

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Article submitted: August 8, 2025; Peer review completed: September 17, 2025; Revised version received: September 20, 2025; Accepted: September 21, 2025; Published: September 25, 2025.

DOI: 10.15376/biores.20.4.9804-9816