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# Reduction of Mould Growth on Beech Timbers Through Optimised Drying and Chemical Protection Strategies

**Ivan Klement, Zuzana Vidholdová * and Tatiana Vilkovská**

Department of Wood Technology, Faculty of Wood Sciences and Technology, Technical University in Zvolen, T.G. Masaryka 24, 96001 Zvolen, Slovakia; klement@tuzvo.sk (I.K.); tatiana.vilkovska@tuzvo.sk (T.V.)
* Correspondence: zuzana.vidholdova@tuzvo.sk

**Abstract**

This study investigates strategies to reduce mould growth on steamed beech wood by evaluating drying-based and fungicide-based protection approaches. The drying-based approach focused on optimising the temperature of warm-air drying parameters to control moisture content and limit mould development. The fungicide-based approach involved testing selected agents, including 3-iodo-2-propynyl butyl carbamate, boric acid, quaternary ammonium compounds, and nano-ZnO, for their effectiveness in preventing mould formation. Mould growth was assessed by macroscopic observation and classified according to standardised intensity levels. The results indicate that adjusting drying parameters alone is insufficient to prevent mould growth, whereas specific fungicide treatments provide effective surface protection. These findings offer practical guidance for minimising mould development on beech wood during drying and storage.

**Keywords:** beech; mould; artificial wood drying; drying parameters; fungicide

## 1. Introduction

In primary hardwood processing, hydrothermal treatment, commonly known as steaming, is widely employed to modify wood properties, particularly in species such as European beech (*Fagus sylvatica* L.) [1–6]. This treatment combines elevated temperature and moisture, inducing significant physical, mechanical, and chemical changes in wood [7]. These include plasticisation of the cell wall, redistribution of extractives, and modifications in the lignin–carbohydrate complex, particularly through partial depolymerisation of hemicelluloses and condensation reactions in lignin [8,9]. Acetic acid is formed through the cleavage of acetyl groups in hemicelluloses, while 2-furaldehyde is produced via dehydration of monosaccharides, mainly D-xylose. These transformations contribute to the mild acetic odour typically associated with steamed beech wood. As a result, hydrothermal treatment improves colour uniformity and workability, making it a standard process in beechwood utilisation [5,10–12]. Colour change is most rapid at the onset of steaming and slows as the treatment progresses. The effectiveness of colour equalisation depends on the temperature, moisture content of wood and duration of hydrothermal treatment, which define the specific "mode" of steaming. Following the steaming process, the wood undergoes drying, and fresh beech wood generally exhibits more even and intense colouration compared to partially pre-dried material.

However, alongside these technological advantages, hydrothermal treatment alters the biological durability of wood. The degradation of hemicelluloses, the formation of low-molecular-weight carbohydrates, and changes in pH may increase the availability

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of nutrients for microorganisms [7,13,14]. Consequently, treated wood can become more susceptible to colonisation by mould and staining fungi, particularly under conditions of elevated moisture. Early studies [15] demonstrated that short-term steaming at 100–160 °C does not prevent colonisation by blue stain fungi, and wood remains susceptible after re-moistening regardless of prior drying intensity. Recent findings [16] further indicate that steaming at temperatures of 105 and 120 °C does not significantly improve resistance against wood-decaying fungi. Experimental studies on beech wood exposed to brown-rot (*Coniophora puteana* (Schum ex Fr) Karsten) and white-rot (*Trametes versicolor* (L.) Lloyd) fungi have shown that both untreated and hydrothermally treated wood exhibit high mass losses, typically exceeding the threshold for non-durable materials. While false heartwood demonstrates slightly higher natural resistance due to its higher extractives content and reduced nutrient availability, hydrothermal treatment tends to reduce these natural differences and may even increase the biological susceptibility of certain wood zones. These effects are attributed primarily to the degradation of hemicelluloses and the formation of readily available low-molecular-weight carbohydrate fractions, which can serve as an immediate nutrient source for fungal metabolism.

While these fungi usually remain superficial and do not significantly interfere with further processing, inadequate storage or drying can promote additional growth, including *Penicillium* species responsible for blue–green–black staining that compromises aesthetic quality [13,17]. Wood moisture content and drying processes significantly influence the susceptibility of timber to biological deterioration, such as fungal and mould growth. The influence of post-treatment drying conditions has also been identified as a critical factor governing fungal colonisation. In study [18], it was shown that mould growth on sapwood boards is strongly affected by drying temperature and stacking configuration. Boards dried at moderate temperatures exhibited higher mould growth, while stacking promoted the migration of soluble nutrients toward the wood surface. Similarly, study [19] reported that mould may initiate earlier on kiln-dried timber than on air-dried wood due to rapid moisture gradients driving nutrient redistribution to the surface layer. These results highlight the importance of drying regimes in maintaining wood quality and resistance to biodeterioration under service conditions.

In addition to nutrient availability, hydrothermal treatment modifies the hygroscopic behaviour of wood, influencing equilibrium moisture content and sorption dynamics. The treatment may increase moisture absorption, which, if not properly controlled, creates conditions favourable for fungal proliferation. Inadequate drying, rapid kiln exposure, or high ambient humidity further facilitate mould growth [20]. Strategies such as careful control of drying conditions, management of nutrient migration to surface layers, and the application of fungicidal coatings can mitigate these effects, although surface damage or ineffective preservative penetration may compromise protection. More broadly, wood is a widely used construction material due to its favourable mechanical properties and relatively low environmental footprint [21].

Preventive strategies include both physical and chemical approaches. Optimised drying schedules can reduce the time wood remains within critical moisture ranges for fungal growth, while appropriate stacking and airflow can limit nutrient accumulation at the surface. Nevertheless, susceptibility to biodeterioration, particularly under elevated moisture conditions, remains a significant challenge. Mould and decay fungi not only affect structural integrity but may also pose health risks in humid environments [20,22]. Moisture content is a key factor governing fungal colonisation and decay. Wood modification techniques such as thermal treatment, acetylation, and furfurylation aim to enhance resistance by increasing hydrophobicity and altering moisture behaviour, although the underlying mechanisms are not yet fully understood [23–26]. Studies on beech and Scots

pine indicate that fungal decay often occurs just below the fibre saturation point, with species-specific thresholds [27].

Surface protection using preservative or biocidal coatings is a common approach to mitigate fungal growth on wood products. Standard antifungal evaluation methods, such as EN 15457 [28], ASTM D3273 [29], and ISO 846 [30], have limitations, particularly in accounting for dynamic changes in wood moisture or species-specific fungal responses. A more recent quantitative approach [31] evaluates antifungal efficiency under controlled conditions using mould, emphasising the importance of considering both moisture dynamics and biocidal activity. Understanding the interactions between wood moisture, fungal physiology, and protective treatments is essential for predicting mould growth and developing effective protection strategies. The treatment with biocides may further inhibit fungal colonisation; however, its effectiveness depends on moisture content, penetration, and interactions with the chemically modified wood structure [14,20,22,26].

Despite extensive research on hydrothermal treatment and fungal resistance, the combined effects of post-treatment drying conditions and chemical protection on mould development remain insufficiently understood. In particular, the interaction between moisture dynamics, nutrient redistribution, and surface protection mechanisms in hydrothermally treated beech wood has not been comprehensively quantified.

This study evaluates the effect of drying conditions and chemical protection in steamed beech wood, with the aim of optimising post-treatment processing and enhancing resistance to biodeterioration caused by moulds.

## 2. Materials and Methods

### *2.1. Steaming Process*

The experiment was conducted on beech wood samples (blanks) with dimensions of 56 mm × 65 mm × 200 mm. Steaming was performed in an autoclave (VYVOS, s.r.o., Uherský Brod, Czech Republic) (Figure 1) using a direct pressure steaming process. The samples were exposed to a temperature of 108 °C for a total duration of 6 h.



**Figure 1.** Steaming autoclave used for the treatment of beech wood samples.

After steaming, the average moisture content of the samples was determined by the gravimetric method in accordance with STN 49 0103 [32].

### 2.2. Approaches to Reducing Surface Mould Growth

After steaming, the samples were treated using two different approaches to reduce surface mould growth: a drying-based approach and a fungicide-based approach. The experimental design is shown in Figure 2.

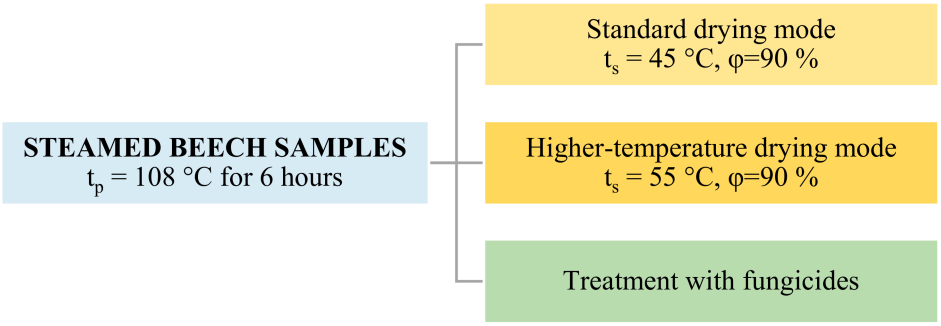



**Figure 2.** Schematic representation of the experimental design, including drying-based regimes and fungicide treatment.

Beech wood samples of two different dimensions were prepared depending on the applied treatment. Samples intended for drying experiments had dimensions of 56 mm× 65 mm× 200 mm (width × thickness × length). Samples intended for chemical treatment were prepared according to STN 49 0604 [33], with dimensions of 10 mm× 5 mm× 50 mm (width × thickness × length).

#### 2.2.1. Drying-Based Approach

In the drying-based approach, samples were exposed to controlled artificial drying regimes under high relative humidity conditions. Two warm-air drying modes were applied, differing in drying air temperature and, consequently, in the intensity of water evaporation. The critical stage for mould development occurs during drying from the initial moisture content to an average moisture content of approximately 20%. Therefore, the samples were dried to a final moisture content of 20%. In the first group, a drying mode commonly used in practice for steamed wood (standard mode) was applied. The second group of samples was dried using a higher-temperature drying mode.

The parameters of the applied drying modes and the calculated maximum drying gradients for different initial wood moisture contents are presented in Table 1. This drying mode was designed so that the drying gradient (U) in the monitored section of drying (down to 20% moisture content) would be approximately the same as in the first (standard) drying mode, while avoiding damage to the dried samples due to internal stresses. The speed of the drying environment flow was constant and was measured at the start of the drying process between samples. The flow speed value was 1.9 ± 0.1 m·s$^{-1}$.

**Table 1.** Parameters of the drying modes and the maximum drying gradients for different initial wood moisture contents.

| Drying Mode | Parameter of Drying Air | | | Maximum Drying Gradient U (–) for Initial Wood Moisture Content | | |
|---|---|---|---|---|---|---|
| | Temperature (°C) | Relative Humidity (%) | Equilibrium Moisture Content (%) | 60 | 55 | 50 |
| Standard mode | 45 | 90 | 18.0 | 3.3 | 3.1 | 2.8 |
| Higher-temperature drying mode | 55 | 90 | 17.7 | 3.4 | 3.1 | 2.8 |

Drying was carried out in a laboratory humidity chamber (Memmert HCP 108; manufactured by Memmert GmbH + Co. KG in Schwabach, Germany) (Figure 3). At regular intervals (24 h), two test samples were weighed to determine their current moisture content. The samples were quickly removed from the chamber to minimise disruption of the drying parameters. After the samples were weighed, they were returned to the same position. The chamber was turned on and kept closed during the weighing of the samples.




**Figure 3.** Humidity chamber used for the drying of steamed samples.

#### 2.2.2. Fungicide-Based Approach

In the fungicide-based approach, samples were treated with chemical biocidal agents to prevent mould development by dipping for 10 min. The fungicides included:

- 3-iodo-2-propynyl butyl carbamate—applied as 1% *w*/*v* in propanol [34], (mark: IPBC),
- Boric acid—applied as 3% *w*/*v* in distilled water [35], (mark: $H_3BO_3$),
- Quaternary ammonium compounds in the form of: I. alkylbenzyldimethylammonium chloride—applied as 3% *w*/*v* in distilled water [36], (mark: BAC); II. benzyl–C12–19-alkyldimethylammonium chloride—applied as a concentrate of commercial preservative that declares a portion of active ingredient < 2.5% [37], (mark: Plesnistop),
- Nano zinc oxide—applied as 1% *w*/*v* aqueous suspension with a nominal particle size < 100 nm [38], (mark: nano ZnO). The suspension was prepared by dilution in water and mechanically mixed prior to application. No additional stabilisation procedure was applied, which may have led to partial agglomeration of nanoparticles.

### *2.3. Evaluation of the Surface Mould Growth*

Surface mould growth on steamed samples during the drying process was visually evaluated separately on longitudinal surfaces (A–D), not strictly corresponding to radial or tangential directions, and on cross-sectional surfaces (1–2) on days 1, 5, 9, 11, 15, and 18.

For the fungicide-treated steamed samples, mould tests were conducted in Petri dishes. Two dishes were prepared per tested substance, each containing four treated samples and one control sample (steamed, untreated). The samples were inoculated with an aqueous spore suspension of *Penicillium* spp., obtained from a wood-processing facility producing steamed wood, and subsequently purified under laboratory conditions to establish a pure culture. The dishes were incubated at 22 ± 2 °C for 28 days in a climate chamber (Memmert model 410; manufactured by Memmert GmbH + Co. KG in Schwabach, Germany), and mould growth was assessed on days 7, 14, and 28.

The surface mould growth on all samples was visually evaluated following the classification specified in the standard STN 49 0604 [33] according to Table 2.

**Table 2.** Classification of the degree of mould growth according to the standard STN 49 0604 [33].

| Degree | Macroscopic Observation of Mould Growth |
|---|---|
| 0 | Surface of the test sample free from infection |
| 1 | Surface of the test sample is occasionally infected up to 10% |
| 2 | Surface of the test sample is lightly covered with mould up to 25% of the area |
| 3 | Surface of the test sample is regularly covered with mould up to 50% of the area |
| 4 | Surface of the test sample is heavily and uniformly covered with weak or intense mould growth |

### 2.4. Statistical Analysis

The degree of mould growth was evaluated using an ordinal rating scale (0–4). Due to the non-continuous and non-normally distributed nature of the data, non-parametric statistical methods were applied. Differences between treatments were assessed using the Kruskal–Wallis test. When statistically significant differences were detected, pairwise comparisons were performed using Dunn's post hoc test with appropriate correction for multiple comparisons. Statistical significance was evaluated at a level of $\alpha = 0.05$.

## 3. Results and Discussion

### 3.1. Moisture Content Before and After Drying

The average moisture content of the steamed beech samples before drying was $w_p = 53 \pm 1.2\%$. The average moisture loss of the samples over time, depending on the applied drying modes, is presented in Figure 4, illustrating the drying behaviour and rate differences between the standard and elevated temperature drying modes.

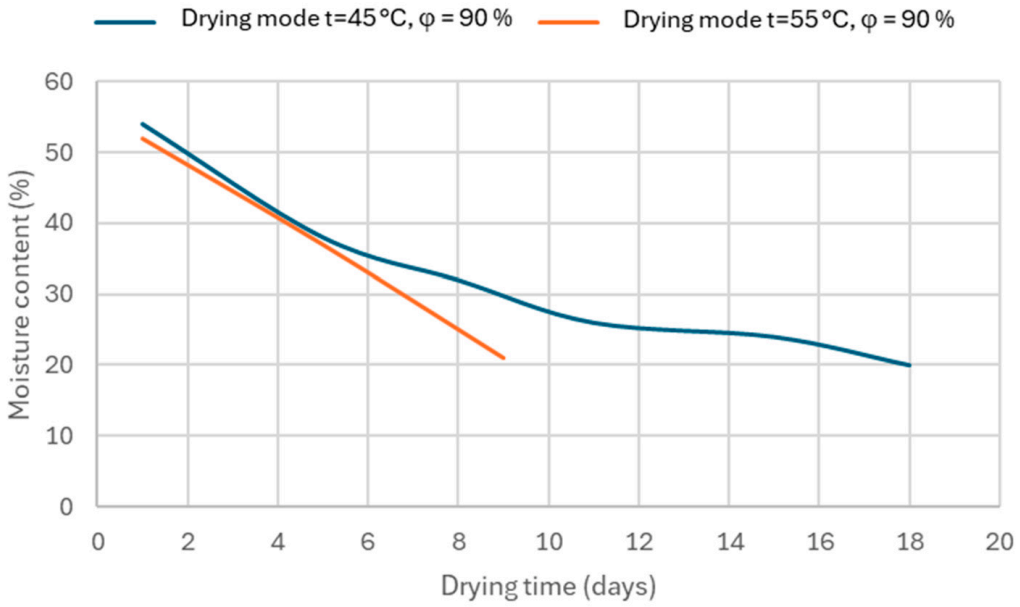



**Figure 4.** Drying curves for the applied modes. Note: $w_p$ refers to the moisture content at the start of the drying process.

### 3.2. Mould Growth Under Artificial Drying

The total drying time was 18 days for the standard drying mode and 9 days for the elevated-temperature mode. During the drying process, visual assessments of mould growth on the surface of the samples were conducted at regular time intervals. Table 3

shows the average mould growth levels on the surface of steamed beech wood during drying using the standard mode and the mode with an elevated temperature.

**Table 3.** Mould-resistance rating for steamed beech specimens with a drying-based approach.

| Surfaces ** | | | Degree of Mould Growth (1–4) * | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Standard Drying Mode $t_s$ = 45 °C, φ = 90% | | | | | | Higher-Temperature Drying Mode $t_s$ = 55 °C, φ = 90% | | |
| | | | Day 1 | Day 5 | Day 9 | Day 11 | Day 15 | Day 18 | Day 1 | Day 5 | Day 9 |
| Longitudinal surfaces | A | Avg. | 0.00 | 3.00 | 3.33 | 3.33 | 3.33 | 3.33 | 0.00 | 2.67 | 3.33 |
| | | SD | 0.00 | 1.26 | 1.21 | 1.21 | 1.21 | 1.21 | 0.00 | 0.82 | 0.52 |
| | B | Avg. | 0.00 | 2.67 | 2.83 | 2.83 | 2.83 | 2.83 | 0.00 | 2.00 | 3.00 |
| | | SD | 0.00 | 1.37 | 1.47 | 1.17 | 1.17 | 1.17 | 0.00 | 0.00 | 0.00 |
| | C | Avg. | 0.00 | 1.67 | 1.67 | 1.67 | 1.67 | 1.67 | 0.00 | 1.33 | 2.00 |
| | | SD | 0.00 | 0.82 | 0.82 | 0.82 | 0.82 | 0.82 | 0.00 | 0.52 | 0.00 |
| | D | Avg. | 0.00 | 1.33 | 1.33 | 1.33 | 1.33 | 1.33 | 0.00 | 2.00 | 3.33 |
| | | SD | 0.00 | 0.52 | 0.52 | 0.52 | 0.52 | 0.52 | 0.00 | 0.00 | 0.52 |
| Cross-sectional surfaces | 1 | Avg. | 0.00 | 3.50 | 4.00 | 4.00 | 4.00 | 4.00 | 0.00 | 4.00 | 4.00 |
| | | SD | 0.00 | 0.84 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| | 2 | Avg. | 0.00 | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 | 0.00 | 4.00 | 4.00 |
| | | SD | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |

Notes: * Values represent the mean (Avg.) and standard deviation (SD) of six samples. ** For longitudinal surfaces, "A" corresponds to the top face, "B" and "D" to the lateral faces, and "C" to the bottom face of the specimen. For cross-sectional surfaces, "1" and "2" correspond to the end-grain surfaces.

The results indicate that the intensity of mould growth on various surfaces of the samples differs. For longitudinal surfaces, the "A = top face" experienced the most significant mould growth, while the "C = bottom face" (in contact with the drying rack) had the least. Variability within tested sets, as indicated by the standard deviation (ranging from 0.52 to 1.33 over 18 days), suggests that sample arrangement and spacing during drying may influence air circulation and, consequently, mould growth.

The cross-sectional surfaces (ends of the samples) showed the fastest mould growth in both drying modes, with a mould degree of 3 to 4 by day 5, covering at least 50% or more of the surface (Figure 5).

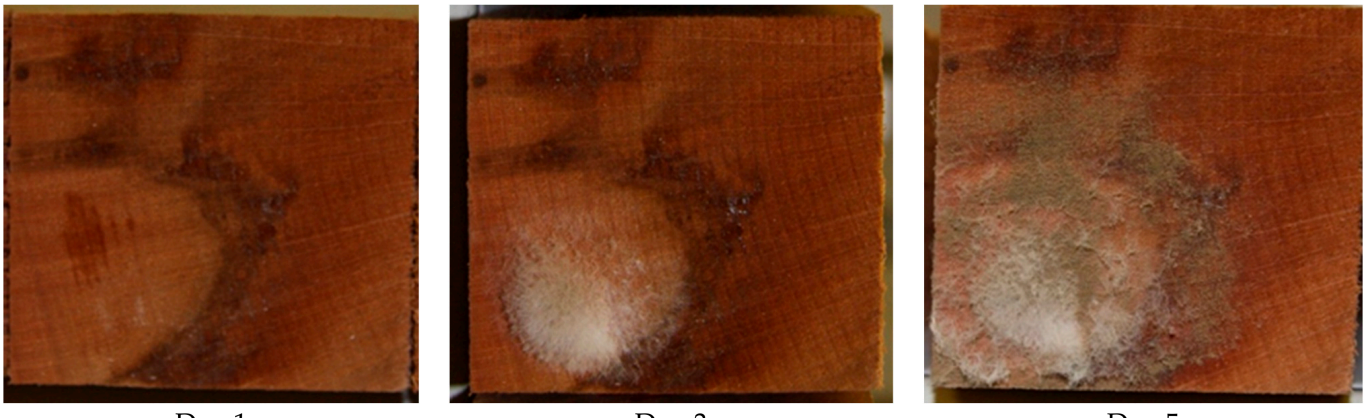



**Figure 5.** Mould growth on the cross-sectional surface of the sample during standard drying conditions ($t_s$ = 45 °C, φ = 90%) after 1, 3, or 5 days.

The observed differences in mould intensity between individual surfaces can be explained by variations in moisture distribution and nutrient availability. The higher susceptibility of the "top" longitudinal surfaces is likely associated with greater exposure to humid air and reduced contact constraints, allowing for increased moisture accumulation. In contrast, the "bottom" surfaces, being in direct contact with the drying rack, experienced limited air access and potentially faster localised drying, thereby reducing conditions favourable for fungal growth. The importance of moisture gradients and surface wetness for mould development has been widely reported [19,39].

The rapid colonisation of cross-sectional surfaces further supports the assumption that these areas are particularly vulnerable due to their anatomical structure. The open cell lumina and exposed vessels facilitate faster moisture uptake and provide easier access to nutrients, which promotes fungal establishment and growth. End-grain surfaces are generally considered the most susceptible to fungal colonisation due to their higher permeability and capillary water transport [14,20,26,40–42].

Increasing the drying temperature to 55 °C had no positive effect on mould reduction. Instead, mould coverage was even greater on radial surfaces by day 9, leading to the experiment's early termination. This trend is clearly illustrated in Figure 6, where a faster increase in mould growth intensity can be observed, particularly on cross-sectional surfaces.

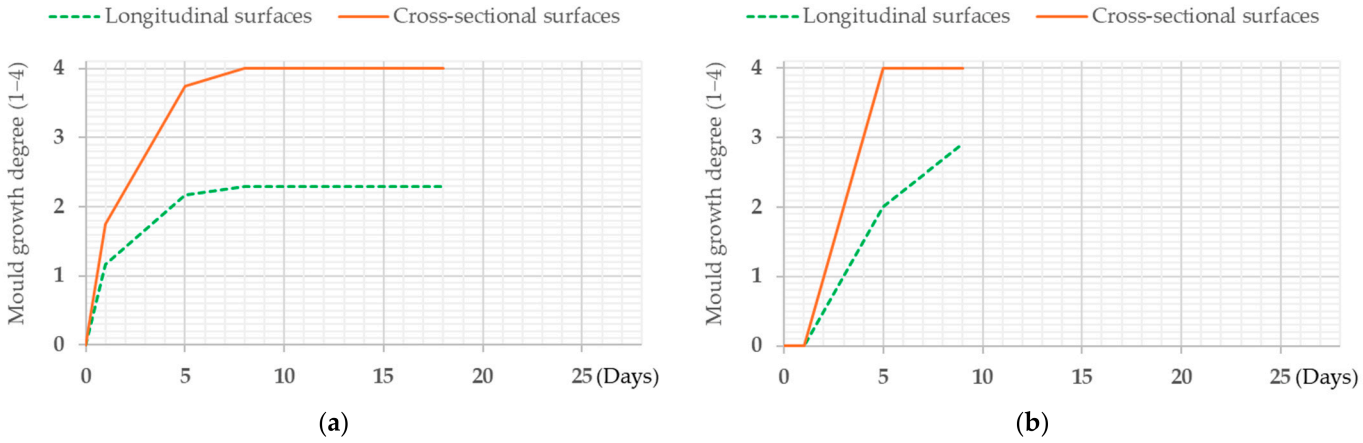



**Figure 6.** Mould growth (0–4) on longitudinal (mean of A–D) and cross-sectional surfaces (mean of 1–2) during drying at 45 °C (**a**) and 55 °C (**b**). Cross-sectional surfaces showed faster colonisation, and increased temperature did not suppress mould growth.

Statistical analysis confirmed significant differences in mould growth intensity between the tested surfaces (Kruskal–Wallis test, H= 56.01, $p < 0.05$) at the end of the test. Post hoc analysis revealed that longitudinal surfaces showed significantly lower mould growth compared to cross-sectional surfaces ($p < 0.001$). In contrast, no statistically significant difference was found between drying temperatures of 45 °C and 55 °C within the same surface type ($p = 1$).

Increasing the drying temperature reduces the equilibrium moisture content and intensifies drying gradients, which may induce wood damage, particularly cracking and surface checking. In contrast, lowering the relative humidity of the drying environment is likely to have an even more pronounced effect on the quality of the dried wood. The absence of a measurable reduction in mould growth at an elevated drying temperature (55 °C) indicates that temperature alone is not a controlling factor under conditions of high relative humidity. Instead, higher temperatures may promote the migration of soluble carbohydrates and degradation products toward the wood surface, thereby increasing nutrient availability for mould fungi. This interpretation is supported by study [18], which demonstrated that drying regimes play a key role in nutrient redistribution and

subsequent susceptibility to mould colonisation. Comparable mechanisms have been reported in studies on wood modification, where thermal and hydrothermal treatments enhance the availability of low-molecular-weight compounds serving as substrates for microbial growth [7,16,26]. Moreover, the results align with study [15], where the author reported that heating does not necessarily prevent colonisation with blue stain fungi, particularly when wood is subsequently exposed to favourable moisture conditions. This is further supported by more recent experimental studies showing that mould fungi are often the first colonisers of wood under elevated humidity and can rapidly develop even on previously treated or dried material [19,43].

Overall, these findings highlight the complex interaction between temperature, moisture, and nutrient dynamics in determining mould susceptibility. Effective control of mould growth, therefore, requires not only appropriate temperature regimes but also careful management of relative humidity, airflow, and drying kinetics to limit surface moisture and nutrient accumulation. This is in agreement with predictive models of mould growth, which identify relative humidity and exposure time as the dominant factors governing fungal development on wood surfaces [40,44].

### 3.3. Mould Growth After Fungicide Treatment

Among the biocides applied to steamed samples, the most effective in preventing visible mould growth were 1% 3-iodo-2-propynyl butyl carbamate solution and 3% boric acid. During the first 14 days, no mould was observed on the sample surfaces (Table 4, Figures 7 and 8). The data showed low within-group variability due to consistent responses across replicates. By day 28, samples treated with boric acid showed slight mould growth (degree 1). These results demonstrate that both biocides provide long-term surface protection, even in contaminated environments such as wood-processing facilities.

**Table 4.** Mould-resistance rating for steamed beech specimens treated with fungicides.

| Active Ingredient | | Degree of Mould Growth (1–4) * | | |
|---|---|---|---|---|
| | | Day 7 | Day 14 | Day 28 |
| 3-iodo-2-propynyl butyl carbamate | Avg. | 0.00 | 0.00 | 0.00 |
| | SD | 0.00 | 0.00 | 0.00 |
| Boric acid | Avg. | 0.00 | 0.00 | 0.63 |
| | SD | 0.00 | 0.00 | 0.74 |
| Alkyl benzyl dimethylammonium chloride | Avg. | 0.00 | 1.13 | 2.00 |
| | SD | 0.00 | 0.83 | 1.07 |
| Benzyl–C12–19-alkyldimethylammonium chloride | Avg. | 0.44 | 3.89 | 4.00 |
| | SD | 0.00 | 0.35 | 0.00 |
| Nano zinc oxide | Avg. | 1.89 | 3.00 | 3.00 |
| | SD | 0.92 | 0.00 | 0.00 |
| Without treatment (Control) | Avg. | 4.00 | 4.00 | 4.00 |
| | SD | 0.00 | 0.00 | 0.00 |

Notes: * Values represent the mean (Avg.) and standard deviation (SD) of eight samples.

The 3% solution of alkyl benzyl dimethylammonium chloride completely suppressed *Penicillium* spp. growth for the first seven days; thereafter, light mould growth appeared on some samples, corresponding to degrees 1–2 (Table 4, Figures 7 and 9). Similarly, benzyl–C12–19-alkyldimethylammonium chloride-treated samples showed delayed but ultimately pronounced mould development. The 1% ZnO nanoparticle suspension reduced surface mould growth to degree 3 within 14–28 days of the test.

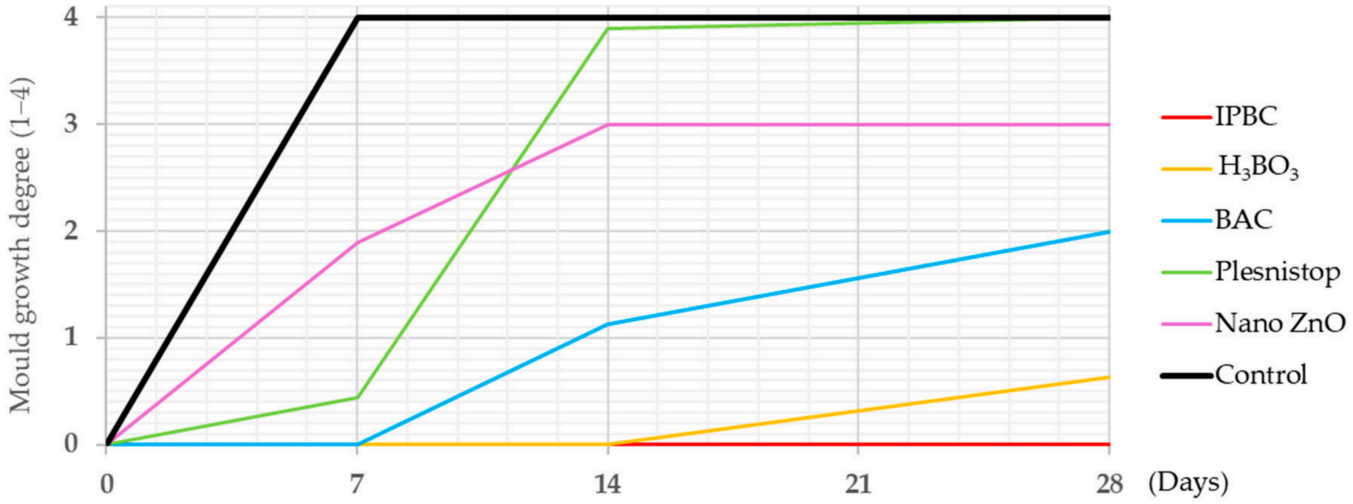



**Figure 7.** Degree of mould growth on samples of steamed beech wood after fungicide treatment over 28 days.

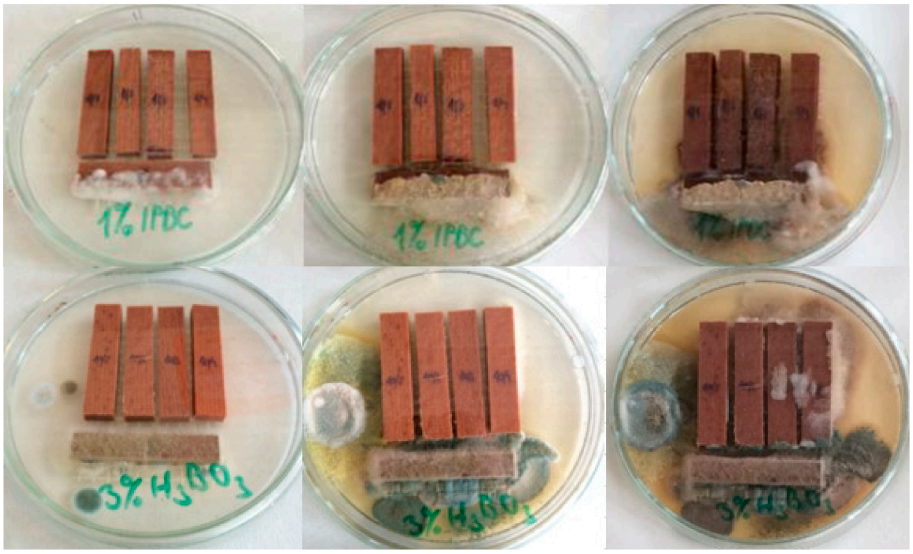



**Figure 8.** The mould growth on top surfaces of steamed beech wood after fungicide treatment with 3-iodo-2-propynyl butyl carbamate (**a**) and boric acid (**b**) at 7, 14 and 28 days.

The degree of mould growth at the end of the test differed significantly among treatments (Kruskal–Wallis test, H = 44.51, $p < 0.001$). The post hoc analysis revealed that IPBC significantly reduced mould growth compared to most other treatments, while no significant difference was observed between 3-iodo-2-propynyl butyl carbamate and boric acid. The highest mould growth was observed in the control and benzyl–C12–19-alkyldimethylammonium chloride groups, which did not differ significantly from each other.

Carbamate-, quaternary ammonium compound- and boron-based fungicides are widely recognised as traditional wood preservatives with well-established efficacy [14,45,46]. Boric acid, containing trivalent boron compounds, has been used for over 50 years for its fungicidal, insecticidal, and fire-retardant properties. Compared to other fungicides, boric acid is considered environmentally favourable and is a water-soluble, non-fixed wood preservative [47]. This lack of fixation represents a major limitation, as boron compounds can be readily leached under conditions of elevated humidity or water exposure, leading to a rapid decrease in their protective efficacy over time. Preservatives based on 3-iodo-2-propynyl

butyl carbamate are intended for non-structural, aboveground application and are not used for pressure-treating applications [46]. Alkylbenzyldimethylammonium chloride, also known as benzalkonium chloride, is an organic salt classified as a quaternary ammonium compound and is used as a preventive fungicide and disinfectant. It can also function as a cleaning agent without notably affecting the wood fibres or the chemical composition of cellulose [48]. However, when treated wood is exposed to moisture, the alkoxymethyl substituents present in quaternary ammonium compounds may leach or detoxify, reducing their surface concentration and allowing mould growth to resume [49]. In addition, their predominantly surface-active mode of action and limited penetration into deeper wood structures may further contribute to reduced long-term protection. This explains why both quaternary ammonium compounds used in this study effectively suppressed mould only during the first 7 days, after which growth (degrees 1–4) was observed.

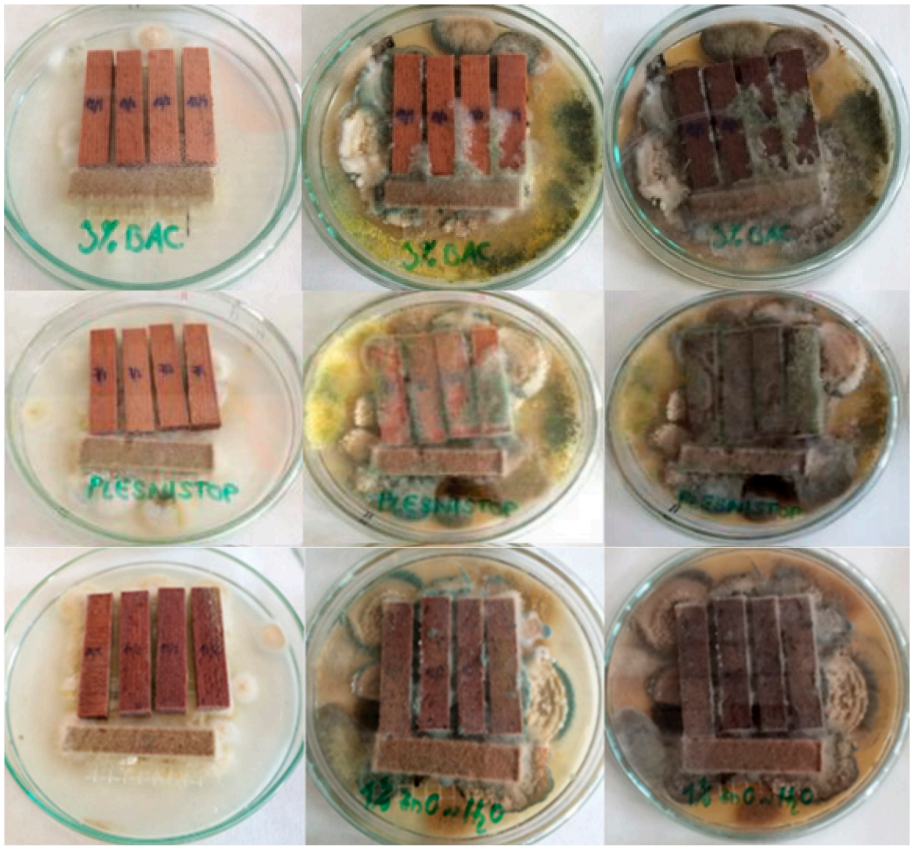



**Figure 9.** The mould growth on top surfaces of steamed beech wood after fungicide treatment with alkylbenzyldimethylammonium chloride (**a**), benzyl–C12–19-alkyldimethylammonium chloride (commercial preservative) (**b**), and nano ZnO (**c**), at 7, 14 and 28 days.

The anti-mould efficiency of ZnO nanoparticles was relatively low in the present study, which is consistent with previous studies reporting their limited curative effect [50,51]. The reduced performance of nano-ZnO in this study may be attributed to several factors, including limited penetration into the wood lumen structure, insufficient concentration, and possible agglomeration of nanoparticles, which can reduce their effective surface area and antimicrobial activity. ZnO nanoparticles appear to act primarily as fungistatic rather than as fungicidal agents, as they do not fully eliminate the initial inoculum [52]. Furthermore, thermal processes such as steaming and drying can induce the migration of low-molecular-weight nutrients (e.g., sugars and other extractives) toward the wood surface. These compounds may subsequently serve as readily available substrates for mould growth,

counteracting the potential inhibitory effect of elevated drying temperatures. However, recent research suggests that nano-based compounds may still offer significant potential as preventive agents, particularly when optimised in terms of formulation, particle size, or when combined with other biocides. Nano-based antifungal agents, such as $TiO_2$, ZnO, and $Ag/TiO_2$ nanocomposites, can inhibit mould colonisation and wood-decay fungi through synergistic photocatalytic activity and hydrophobic modification of the wood structure [53–55]. However, their effectiveness strongly depends on proper dispersion and stabilisation, which are critical factors influencing their interaction with fungal cells and overall performance.

In parallel, natural bioactive compounds, such as extractives and essential oils, have been studied as renewable antifungal agents. Their volatile phenolic constituents disrupt fungal cell membranes, and nanoencapsulation strategies can improve their stability and durability on wood substrates [55–57]. These substances are particularly attractive because they preserve the natural colour of steamed wood, avoiding the discolouration often associated with conventional treatments, and they may also contribute to improved workplace hygiene by reducing airborne spores and surface contamination. Consequently, such biocides have the potential to complement or partially replace traditional preservatives, providing effective mould protection while enhancing environmental and occupational safety.

## 4. Conclusions

This study addressed mould growth reduction on beech wood after colour equalisation by steaming process, either by modifying drying temperature or applying chemical protection using selected fungicidal agents. The following conclusions can be drawn from the experimental results:

- Increasing the drying temperature from 45 to 55 °C had no significant effect on reducing mould growth on steamed wood.
- The most effective treatments were 3-iodo-2-propynyl butylcarbamate (1% solution) and boric acid (3% aqueous solution), both of which completely suppressed mould growth on the wood surface.
- For short-term protection, a 3% aqueous solution of alkylbenzyldimethylammonium chloride, the commercial product containing benzyl-C12–16-alkyldimethylammonium chloride at concentrations <2.5%, and a 1% suspension of nano-zinc oxide were also found to be effective.

These findings confirm that chemical protection is essential for improving the mould resistance of steamed beech wood.

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## References


1. Yilgor, N.; Unsal, O.; Kartal, S.N. Physical, mechanical, and chemical properties of steamed beech wood. *For. Prod. J.* **2001**, *51*, 89–94.
2. Harris, R.A.; Schroeder, J.G.; Addis, S.C. Steaming of red oak prior to kiln drying: Effects on moisture movement. *For. Prod. J.* **1989**, *39*, 70–72.
3. Varga, D.; van der Zee, M.E. Influence of steaming on selected wood properties of four hardwood species. *Holz Roh Werkst.* **2008**, *66*, 11–18. [CrossRef]
4. Hansmann, C.; Stingl, R.; Teischinger, A. Inquiry in beech wood processing industry concerning red heartwood. *Wood Res.* **2009**, *54*, 1–12.
5. Tolvaj, L.; Nemeth, R.; Varga, D.; Molnar, S. Colour homogenisation of beech wood by steam treatment. *Drewno* **2009**, *52*, 5–17.
6. Klement, I.; Huráková, T. Determining the influence of sample thickness on high-temperature drying of beech wood (*Fagus sylvatica* L.). *BioResources* **2016**, *11*, 5424–5434. [CrossRef]
7. Ali, M.R.; Abdullah, U.H.; Ashaari, Z.; Hamid, N.H.; Hua, L.S. Hydrothermal modification of wood: A review. *Polymers* **2021**, *13*, 2612. [CrossRef]
8. Timar, M.C.; Varodi, A.; Hacibektasoglu, M.; Campean, M. Color and FTIR analysis of chemical changes in beech wood (*Fagus sylvatica* L.) after light steaming and heat treatment. *BioResources* **2016**, *11*, 8325–8343. [CrossRef]
9. Geffert, A.; Výbohová, E.; Geffertová, J. Characterization of the changes of colour and some wood components on the surface of steamed beech wood. *Acta Fac. Xylologiae Zvolen* **2017**, *59*, 49–57. [CrossRef]
10. Klement, I.; Vilkovská, T.; Vilkovský, P.; Uhrín, M. Comparison of pressure and atmospheric steaming processes and their effects on selected properties of beech wood (*Fagus sylvatica* L.). *Appl. Sci.* **2025**, *15*, 13066. [CrossRef]
11. Dudiak, M.; Dzurenda, L. The effect of sunlight on the color change of steamed birch wood. *Acta Fac. Xylologiae Zvolen* **2023**, *65*, 35–43. [CrossRef]
12. Dudiak, M. Evaluation of the process of steaming beech sapwood and false heartwood with saturated water steam in terms of acidity changes and color. *Forests* **2025**, *16*, 864. [CrossRef]
13. Trebula, P.; Klement, I. *Sušenie a hydrotermická úprava dreva (Drying and Hydrothermal Treatment of Wood)*; Technical University in Zvolen: Zvolen, Slovakia, 2002.
14. Reinprecht, L. *Wood Deterioration, Protection, and Maintenance*; John Wiley & Sons: Chichester, UK, 2016.
15. Seehann, G. The effect of drying and heating softwoods on the growth of bluestain fungi. *Holz Roh Werkst.* **1965**, *23*, 341–347. [CrossRef]
16. Vidholdová, Z.; Dudiak, M.; Slabejová, G.; Výbohová, E. Hydrothermal Modification of Beech Wood. In *Wood Science and Processing Engineering*; IntechOpen: London, UK, 2026.
17. Betina, V. *Mykotoxíny—Chémia, Biológia, Ekológia (Mycotoxins—Chemistry, Biology, Ecology)*; Alfa: Bratislava, Slovakia, 1990.
18. Sehlstedt-Persson, M.; Karlsson, O.; Wamming, T.; Morén, T. Mold growth on sapwood boards exposed outdoors: The impact of wood drying. *For. Prod. J.* **2011**, *61*, 170–179. [CrossRef]
19. Johansson, P.; Wamming, T.; Bok, G.; Edlund, M.L. Mould growth on kiln-dried and air-dried timber. *Eur. J. Wood Wood Prod.* **2013**, *71*, 473–481. [CrossRef]
20. Zabel, R.A.; Morrell, J.J. *Wood Microbiology: Decay and Its Prevention*, 2nd ed.; Elsevier: Amsterdam, The Netherlands, 2020.
21. Hammond, G.P.; Jones, C.I. Embodied energy and carbon in construction materials. *Proc. Inst. Civ. Eng. Energy* **2008**, *161*, 87–98. [CrossRef]
22. Rowell, R.M. (Ed.) *Handbook of Wood Chemistry and Wood Composites*; CRC Press: Boca Raton, FL, USA, 2005.
23. Kutnik, M.; Suttie, E.; Brischke, C. European standards on durability and performance of wood and wood-based products—Trends and challenges. *Wood Mater. Sci. Eng.* **2014**, *9*, 122–133. [CrossRef]
24. Sonderegger, W.; Niemz, P. Thermal conductivity and water vapour transmission properties of wood-based materials. *Eur. J. Wood Wood Prod.* **2009**, *67*, 313–321. [CrossRef]
25. Sonderegger, W.; Glaunsinger, M.; Mannes, D.; Volkmer, T.; Niemz, P. Investigations into the influence of wood coatings on water diffusion determined by neutron imaging. *Eur. J. Wood Wood Prod.* **2015**, *73*, 793–799. [CrossRef]
26. Sandberg, D.; Kutnar, A.; Karlsson, O.; Jones, D. *Wood Modification Technologies: Principles, Sustainability, and the Need for Innovation*; CRC Press: London, UK, 2021.
27. Vilkovský, P.; Klement, I.; Vilkovská, T. The Impact of the Log-Sawing Patterns on the Quantitative and Qualitative Yield of Beech Timber (*Fagus sylvatica* L.). *Appl. Sci.* **2023**, *13*, 8262. [CrossRef]
28. *EN 15457*; Wood Preservatives—Laboratory Method for Determining the Preventive Effectiveness against Mould Fungi. European Committee for Standardization: Brussels, Belgium, 2022.

29. *ASTM D3273*; Standard Test Method for Resistance to Growth of Mold on the Surface of Interior Coatings in an Environmental Chamber. ASTM International: West Conshohocken, PA, USA, 2021.
30. *ISO 846*; Plastics—Evaluation of the Action of Microorganisms. International Organization for Standardization: Geneva, Switzerland, 2019.
31. Myronycheva, O.; Kim, I.; Karlsson, O.; Kiurcheva, L.; Jacobsson, P.; Sandberg, D. Evaluation of the antifungal efficiency of coatings on wood. *Wood Sci. Technol.* **2025**, *59*, 12. [CrossRef]
32. *STN 49 0103*; Zisťovanie vlhkosti pri fyzikálnych a mechanických skúškach (Moisture Detection in Physical and Mechanical Tests). Slovak Institute of Technical Standardization: Bratislava, Slovakia, 1979.
33. *STN 49 0604*; Ochrana dreva. Metódy stanovenia biocídnych vlastností ochranných prostriedkov na drevo (Wood Protection. Methods for Determining the Biocidal Properties of Wood Preservatives). Slovak Institute of Technical Standardization: Bratislava, Slovakia.
34. Sigma-Aldrich. Product 521949. Available online: https://www.sigmaaldrich.com/SK/en/product/aldrich/521949 (accessed on 27 March 2026).
35. Sigma-Aldrich. Product b0394. Available online: https://www.sigmaaldrich.com/SK/en/product/sigald/b0394 (accessed on 27 March 2026).
36. Sigma-Aldrich. Product 8.14858. Available online: https://www.sigmaaldrich.com/SK/en/product/mm/814858?srsltid=AfmBOoqvvvjzBIbmB9h4vkBW5TVFQ0qtTNs35mlBtjAA_WCyx4M5O_M7 (accessed on 27 March 2026).
37. Color Company. PLESNISTOP—Protiplesňová Prísada. Available online: https://www.colorcompany.sk/public/manager/source/KBU%202023/KBU%20PLESNISTOP%20Protiplesnova%20prisada%20SK%202022.pdf (accessed on 27 March 2026).
38. Sigma-Aldrich. Product 72107. Available online: https://www.sigmaaldrich.com/SK/en/product/aldrich/721077 (accessed on 27 March 2026).
39. Viitanen, H. *Factors Affecting Mould Growth on Kiln Dried Wood*; VTT Technical Research Centre of Finland: Espoo, Finland, 2001; 8p.
40. Gradeci, K.; Labonnote, N.; Time, B.; Köhler, J. Mould growth criteria and design avoidance approaches in wood-based materials: A systematic review. *Constr. Build. Mater.* **2017**, *150*, 77–88. [CrossRef]
41. Pasanen, A.L.; Kasanen, J.P.; Rautiala, S.; Ikäheimo, M.; Rantamäki, J.; Kääriäinen, H.; Kalliokoski, P. Fungal growth and survival in building materials under fluctuating moisture and temperature conditions. *Int. Biodeterior. Biodegrad.* **2000**, *46*, 117–127. [CrossRef]
42. Broda, M. Natural Compounds for Wood Protection against Fungi—A Review. *Molecules* **2020**, *25*, 3538. [CrossRef]
43. Ryparová, P.; Rácová, Z. Characteristics of mould growth in pine and spruce sapwood and heartwood under fluctuating humidity. *Appl. Sci.* **2024**, *14*, 8417. [CrossRef]
44. Viitanen, H.; Ritschkoff, A.C. *Mould Growth in Pine and Spruce Sapwood in Relation to Air Humidity and Temperature*; Swedish University of Agricultural Sciences: Uppsala, Sweden, 1991; 221p.
45. Reinprecht, L.; Tiralová, Z. Biocides for wood protection—Application in interiors. *Stavebné Mater.* **2007**, *3*, 52–53.
46. Vani, C.N.; Prajwal, S.; Sundararaj, R.; Dhamodaran, T.K. Chemical Preservatives in Wood Protection. In *Science of Wood Degradation and Its Protection*; Sundararaj, R., Ed.; Springer: Singapore, 2022. [CrossRef]
47. Reinprecht, L.; Pánek, M. Fungicidal effectiveness of boron in wood protection products containing ammonium salts. *Acta Fac. Xylologiae Zvolen* **2007**, *49*, 53–62.
48. Salim, E.; Hassan, R.R.A. Alkyl dimethyl benzyl ammonium chloride as a new cleaner for washing treatments for historical printed paper. *Pigment. Resin Technol.* **2024**, *53*, 164–172. [CrossRef]
49. Zabielska-Matejuk, J.; Czaczyk, K. Biodegradation of new quaternary ammonium compounds in treated wood by mould fungi. *Wood Sci. Technol.* **2006**, *40*, 461–475. [CrossRef]
50. Reinprecht, L.; Vidholdová, Z. Growth inhibition of moulds on wood surfaces in the presence of nano zinc oxide and its combinations with polyacrylate and essential oils. *Wood Res.* **2017**, *62*, 37–44.
51. Papadopoulos, A.N.; Bikiaris, D.N.; Mitropoulos, A.C.; Kyzas, G.Z. Nanomaterials and chemical modifications for enhanced key wood properties: A review. *Nanomaterials* **2019**, *9*, 607. [CrossRef]
52. Ardiansyah, R.; Santoso, I. The effect of zinc oxide nanoparticles against ceiling mold isolates. *IOP Conf. Ser. Earth Environ. Sci.* **2020**, *481*, 012017. [CrossRef]
53. Lin, L.; Cao, J.; Zhang, J.; Cui, Q.; Liu, Y. Enhanced anti-mold property and mechanism of Ag/$TiO_2$ wood-based nanocomposites formed by ultrasound- and vacuum-impregnation. *Nanomaterials* **2020**, *10*, 682. [CrossRef]
54. De Filpo, G.; Palermo, A.M.; Rachiele, F.; Nicoletta, F.P. Preventing fungal growth in wood by titanium dioxide nanoparticles. *Int. Biodeterior. Biodegrad.* **2013**, *85*, 217–222. [CrossRef]
55. Woźniak, M. Antifungal agents in wood protection—A review. *Molecules* **2022**, *27*, 6392. [CrossRef]

56. Yang, V.W.; Clausen, C.A. Inhibitory effect of essential oils on decay fungi and mold growth on wood. In *Proceedings of the 103rd Annual Meeting of the American Wood Protection Association*; American Wood Protection Association: Birmingham, AL, USA, 2007; pp. 62–70.
57. Calovi, M.; Zanardi, A.; Rossi, S. Recent advances in bio-based wood protective systems: A comprehensive review. *Appl. Sci.* **2024**, *14*, 736. [CrossRef]

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