

## Article

# Effect of Protective Coatings on Wooden Elements Exposed to a Small Ignition Initiator

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**Abstract:** This paper presents the results of monitoring the behaviour of selected wood species exposed to a small ignition initiator. We specifically aimed to investigate the effect of retardant coating on the combustion process of the wood species spruce (*Picea abies*), red spruce (*Larix decidua*), Scots pine (*Pinus sylvestris*), ash (*Fraxinus excelsior* L.), beech (*Fagus sylvatica*), and oak (*Quercus robur*) when exposed to a small initiator of ignition. At the same time, we studied the effect of different types of fungicidal agents (based on N-(3-aminopropyl)-N-dodecylpropane-1,3-diamine; alkyl (C12–16) dimethylbenzyl ammonium chloride or 3-iodo-prop-2-nylbutylcarbamate) on the effectiveness of a flame retardant (containing ferric phosphate) applied to the selected fungicide-treated wood samples. The experimentally obtained mass-loss and flame-spread results were statistically evaluated using the QtiPlot software program. A significant dependence of mass loss and surface flame spread on wood species was the primary focus. It was only confirmed for the surface-flame-spread variable. The dependence of the effect of fungicide treatment on the effectiveness of the selected retardant was confirmed. Fungicidal coatings with the active ingredient alkyl/benzyl (C12–16) dimethylbenzyl ammonium chloride indicated the lowest mass loss rate and flame spread for all wood samples.

**Keywords:** spruce; red spruce; pine; ash; beech; oak; fungicide coating; fire coating; flame



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## 1. Introduction

Wooden elements have become part of the interior and exterior of building structures [1,2]. However, inappropriate use of wood can also cause problems as wood exhibits considerable variability in physical properties, highly dependent on moisture content and loading duration [3–7].

Well-known theories of wood flammability [8,9] and its limited fire resistance [10–12] compel the implementation of appropriate surface treatment of wooden elements [13]. The purpose of wood surface treatment may vary. A separate group of coatings as protective elements are fungicidal coatings [14]. Fungicidal coatings have become significant due to climate change resulting in increasingly frequent extreme weather events. Moreover, wood as a natural material tends to degrade, not only thermally but also biologically (by the action of insects and wood-destroying fungi). Fire-resistant coatings of wooden elements usually follow as a secondary protective layer [15,16]. Building chemistry offers a wide variety of both types of the above-mentioned substances.

Due to the activity of insects, wood-destroying fungi, or the action of heat [17,18], the properties of wood deteriorate: in particular, its mechanical properties are reduced [19,20]. Measures to prevent inappropriate degradation effects on wood are implemented through appropriate surface treatment.

### Protective Coatings

Wood is a natural biopolymer. Its macroscopic structure consists of features (observable with the naked eye or with a magnifying glass) that form a characteristic pattern on the surface. This structural level mainly defines the external appearance, such as volume, spatial shapes, surface quality, the proportion of sapwood and heartwood, and the proportion of spring and summer wood. It also defines the presence, frequency, and conditions of macroscopic inhomogeneities such as knots, pressure and tension wood, heartwood, resin channels, etc. [21,22]. The wood microstructure presents its anatomical and chemical composition and the movement of fluids in different anatomical directions. The above-mentioned processes are described in detail in the works [19,23,24].

After sawing, the tree loses all the protective mechanisms that existed during its growth, creating a suitable environment for the growth of moulds and fungi, eventually joined by insects. The resistant, flexible, and hard wood loses its properties and turns into organic waste that is a source of nutrients for bacteria and plants [25,26].

Maintaining the stability of the wood mass lies in its appropriate drying and then in suitable surface treatment [27]. One possibility is the application of protective coatings [28–31]. Rot is an irreversible phenomenon that damages the surface of wood. Therefore, it is necessary to protect wooden surfaces with fungicidal coatings.

Fire-retardant substances are predominantly available in the forms of liquid, gel, foam, and powder to suit the materials that vary in physical nature and chemical composition. Most fire retardants act synergically to increase fire protective benefits [32]. As the elements in fire retardants applied to different materials react differently with fire, the selection of fire retardants must respect the type of material [33]. Many papers focus on retardant treatments for wood with detailed explanations of the method of application [34], both inorganic- [35–37] and organic-based [38,39], even vegetable oil-based [40–42].

The research we carried out is aimed at finding a connection between fungicidal coatings and retardant coatings which are applied to the surface of wood.

The aim of the article can be specified in several successive aims. The first subaim was focused on investigating the effect of a retardant coating on the combustion process of the selected wood species, Norway spruce (*Picea abies*), red spruce (*Larix decidua*), Scots pine (*Pinus sylvestris*), common ash (*Fraxinus excelsior* L.), common beech (*Fagus sylvatica*), and English oak (*Quercus robur*), through the action of a small ignition initiator. The second subaim was researching the influence of different types of fungicidal agents on the effectiveness of fire retardants applied to the wood samples presented above. Last but not least, a significant dependence of the effect of the wood's kind and the coating's kind on the mass loss of the samples and the speed of flame propagation on the surface of the wood samples was sought.

## 2. Materials and Methods

### 2.1. Experimental Samples

The sample selection was based on the most frequent use of these wood species in the joinery and carpentry industry (Table 1). From each wood type, 30 samples were prepared with dimensions 250 × 90 × 20 mm. The moisture content of each sample was determined gravimetrically according to the recommendations of [43,44]. The density of the wood samples was determined according to [45].

The group of softwood samples (spruce, red spruce, and pine) has similar applications, namely, in the production of fibreboards, particleboards, plywood, and veneers; it can be used as building and construction timber indoors and outdoors, as well as for ship and mast construction [46]. Hardwood is a feedstock for the furniture industry [47].

The experiments were conducted with 5 fungicide coatings from different manufacturers with different chemical compositions (Table 2) and the flame retardant HRP.

**Table 1.** Wood samples used in the experiment.

Wood	Technical Name	Moisture (%)	Density (kg·m <sup>-3</sup> )	Designation	
Soft	Norway spruce	( <i>Picea abies</i> )	17	380	SM
	Red spruce	( <i>Larix decidua</i> )	15.7	330	SMR
	Scots pine	( <i>Pinus sylvestris</i> )	16	430	BOR
Hard	Common ash	( <i>Fraxinus excelsior</i> L.)	15.8	570	JAS
	Common beech	( <i>Fagus sylvatica</i> )	18.8	570	BUK
	English oak	( <i>Quercus robur</i> )	18	650	DUB

**Table 2.** Characteristics of fungicides and retardant coatings.

Chemical	Type	Appearance	Density (g·cm <sup>-3</sup> )	Component	Amount (%)
FUN [48]	fungicide	Colourless transparent liquid	1.0	N-(3-aminopropyl)-N-dodecylpropane-1,3-diamine(molecular formula C <sub>18</sub> H <sub>41</sub> N <sub>3</sub> )	<3
				lactic acid	<3
				2,2'-oxydiethanol, amines, coco alkyl dimethyl, N-oxides	<2
				propiconazole cypermethrin	<2 <0.25
BOCH FUN [49]	fungicide	Brown odourless liquid	0.99–1.0	alkyl (C12–16) dimethylbenzyl ammonium chloride	<20
				2-(2-butoxyethoxy)ethanol	<2
				phosphoric acid	<0.5
				propiconazole, tebuconazole	<0.3
				N-(3aminopropyl)-N-dodecylpropane-1,3-diamine Cypermethrin	<0.25 <0.1
BOCH [50]	fungicide	Colourless transparent liquid	1.015–1.030	alkyl/benzyl (C12–16) dimethylbenzyl ammonium chloride	<5.3
				boric acid	<5.3
				2-aminoethanol	<2
NAP [51]	fungicide	Colourless transparent liquid of light yellow	0.9–1.10	hydrocarbons of C10-C13 n-alkanes, cycloalkanes, isoalkanes, aromatics	<2
				2-(2-butoxyethoxy)ethanol tebuconazole (ISO) cyclohexanone oxime cypermethrin	
AQUA [52]	fungicide	Whitish liquid	1.01–1.02	D-glucose, oligomers, decyclooctyl glycosides, mixture of 5-chloro-2-methyl-2H-isothiazol-3-one and 2-methyl-2H-isothiazol-3-one	
				propiconazole (ISO)	<1
				3-iodoprop-2-ynylbutylcarbamate	<1
				cypermethrin	<0.1
HRP [53]	flame retardant	Light brown odourless liquid	1.10+/-0.01	ferric phosphate/Iron orthophosphate	< 30%
				citric acid	<1%
				octadecan-1-ol, ethoxylated	<0.5
				reaction to fire	B-s1, d0

The price of protective coatings varies depending on the seller and the size of the package. A 1 kg package of HRP costs around EUR 25–39, a 5 kg package of HRP costs around EUR 87–140. The price of fungicidal coatings is also very different, but they are cheaper than HRP. The prices of fungicidal coatings are approximately one-third the price of HRP. A 1 L package of fungicidal coating costs around EUR 9–13, a 5 L package costs EUR 30–50 [48].

Each of the studied fungicidal coatings can be used indoors (roof structures, floors) and outdoors (roof underlayment, fences, pergolas) [48–52]. The prepared wood samples with fungicidal coatings were stable. The modified surface kept its smooth shape and did not change its colour and consistency.

Manufacturers [48–52] guaranteed washout resistance. High moisture or loading of the coating with water and snow will not affect the quality of the fungicidal coating. Exposure of the product treated with the fungicidal coating to high temperature is not indicated by the manufacturer.

The used flame retardant HRP can be used both indoors and outdoors and cannot be washed off after drying. HRP can be used on material exposed to water and snow and in high moisture environments. The manufacturer [53] indicates the resistance of the treated product by HRP to temperatures higher than 1700 °C, then blackening of the surface of the sample occurs and the fire does not spread.

The composition of coatings varies, but some ingredients are common. Specifically, cypermethrin is a component of every fungicide preparation. It is an insecticidal chemical (based on organic cyanides) used on insects, earthworms, fish, and crustaceans. It persists in the air and on walls and furniture for approximately three months after use in the home [54]. Subsequent application of a protective retardant coating appears suitable and justifiable.

N-(3-aminopropyl)-N-dodecylpropane-1,3-diamine, molecular formula  $C_{18}H_{41}N_3$ , is a biocidal agent with amino linkages (-NH<sub>2</sub>), causing skin burns and eye damage [47,49]. It is part of the FUN and BOCH FUN preparation.

Alkyl (C12–16) dimethylbenzyl ammonium chloride is a mixture of nitrogen cationic surfactants (tensides) belonging to the group of quaternary ammonium salts. It is predominantly used as a biocide and cationic tenside [55].

3-Iodoprop-2-ynyl-butyl carbamate (IPBC) is listed as an active biocidal agent that can cause an allergic reaction [56] and is part of NAP and AQUA.

Propiconazole is a triazole fungicide that contains a five-membered heterocycle with three nitrogen atoms [57]. It is a systemic fungicide, and its mode of action involves the inhibition of ergosterol biosynthesis [58,59].

The experimentally obtained results should confirm the appropriate choice of fungicidal coating as a basis for the selected fire-retardant coating.

HR-PROF is a fire-control product or flame retardant that limits the possibility of ignition and propagation of flame in wooden structures, cassette ceilings, wooden floors, and other products made from wood and cellulose. HR-PROF is used in the interior and exterior. After the application and the drying, it is not washable, does not create fumes at high temperatures, and burned dust is not dispersed into the area. When material treated with the HR-PROF is exposed to temperatures exceeding 1700 °C, its surface will turn black, and the fire quickly stops spreading [53]. HR-PROF is suitable for different wood products (wooden structures, walls, cottages, living quarters, ships, etc.). The retarding effects of phosphates were also confirmed for other cellulose fibres [60].

## 2.2. Preparation of Samples for Monitoring Initiation by a Small Ignition Initiator

The application of coatings to the samples was based on the manufacturers' recommendations. The application is determined in the technical specification supplied together with the coating [48–52]. Coatings were applied using a brush. Verification of the amount of received protective wood coating was carried out for each sample separately by monitoring the amount of used coating sample before and after painting. The difference in the observed

values indicated the reception of a sufficient amount of coating, of course, in accordance with the values set by the manufacturer.

The sample preparation for initiation monitoring was conducted in the Fire Chemistry Laboratory of the Department of Fire Engineering, FBI UNIZA (Figure 1). The steps of treatment, in terms of the precautions regarding OSH [61], followed the specific procedure:

- During the period from 8 October 2021 to 29 October 2021, the mass samples were air-conditioned and then dried (Drying room, Airtechno, Nová Dubnica nad Váhom, Slovakia). The mass was determined using digital scales with an accuracy of 0.01 g (Mettler Toledo, Columbus, OH, USA).
- After the mass was stabilized, the first layer of fungicidal coating was applied. The drying time of the coating was determined by its manufacturer.
- The second layer of fungicide coating was applied after 10 days. After this application, a 2-week period was specified for the coating to mature and the mass to settle. There was a decrease in mass due to the evaporation of water.
- After the above period, two coats of flame retardant were applied. Based on the manufacturer's recommendation, the samples needed to be dried for 3 weeks.



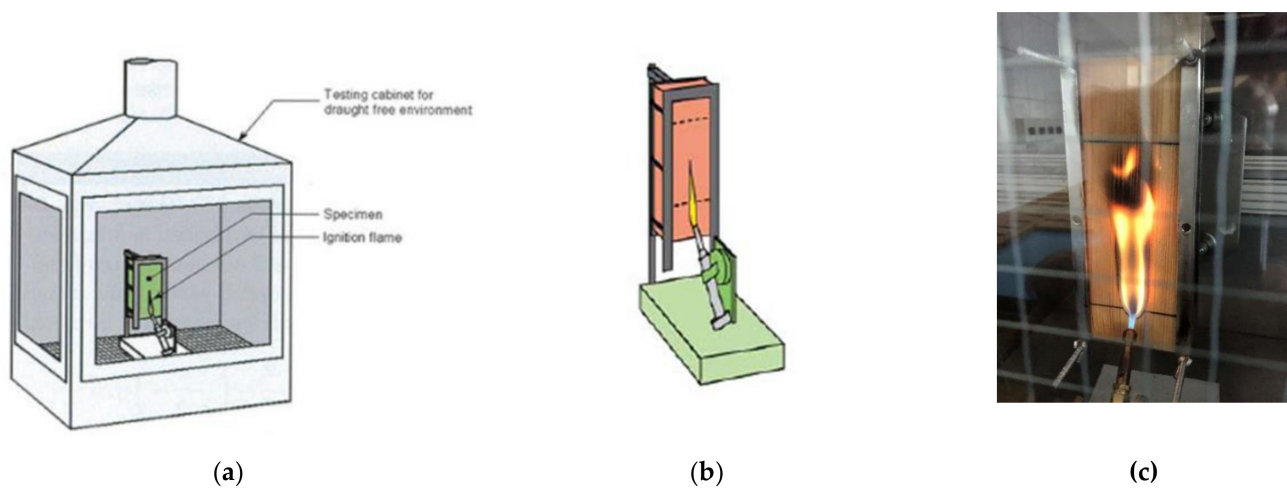
**Figure 1.** Oak sample in the process of applying protective coatings.

Monitoring the mass of the samples in the individual technological steps brought an interesting result: that is, a total decrease in the mass of the test samples (by 6%). All used coatings are water-dilutable. Their application consists of the penetration of the product dissolved in water into the surface structure of the wood [60]. An important element is the stabilization of mass after the second fungicide coating, which has been achieved.

### 2.3. Determination of the Ignitability of Wood Samples by the Action of a Small Ignition Initiator

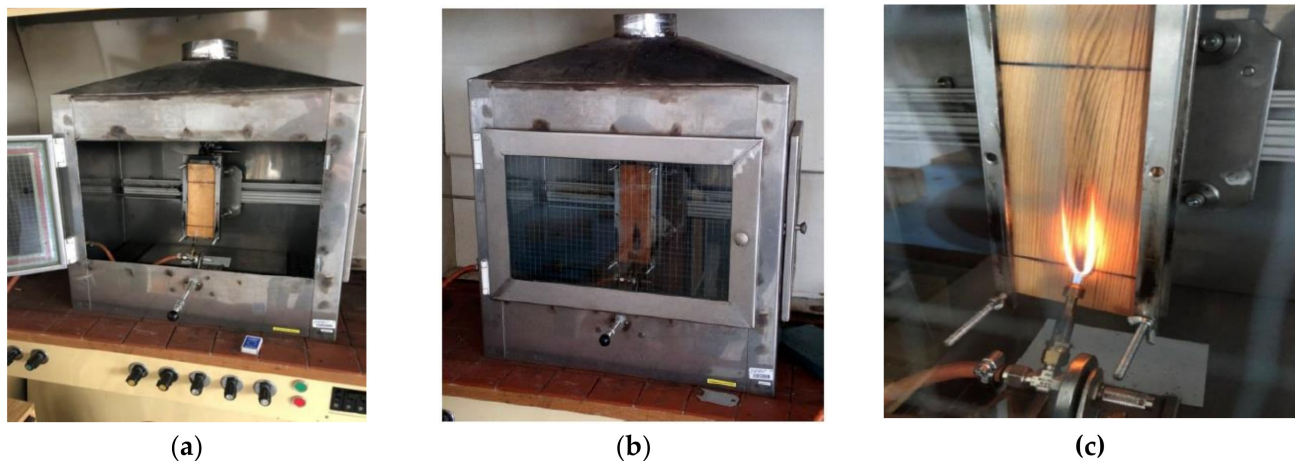
Solid wood panels are rated as building elements according to EN 13353 as D-s2, d0 [62]. The terms of the classification are “reaction to fire D-s2, d0 by [63]”. Reactions to fire testing methods are designed to simulate the fire incipient and growth phases. The purpose is to evaluate how products and materials contribute to the early stages of a fire in terms of ignitability, flame spread, heat release, smoke production, and occurrence of flaming droplets or particles [64]. D-s2, d0 means “combustible materials—medium contribution to fire, with the speed of emission absent or weak during combustion” according to [63]. The priority of the experiment was to monitor the critical parameters of the ignition based on the change in board thickness. Most wood products fall into classes D-s2, and d0 [62]. The 2 tests were conducted for the classification of building products (i.e., wood-based materials) according to EN 13501-1. The first test followed the test method of EN ISO 11925-2 Inflammability of building products with direct exposure to flames and the second test followed the test method of EN 13823 Thermal load from a single burning object [65]. Our research applied the first test.

The experiments were conducted in the Fire Chemistry Laboratory of the Department of Fire Engineering FBI UNIZA. The test method was determined according to STN EN ISO 11925-2 [66] to test the ignitability of building materials due to the influence of a small flame combustion source. The test was performed in a test chamber (Fire Engineering and Expertise Institute, Bratislava, Slovakia) (Figure 2).



**Figure 2.** (a) Test chamber according to STN EN ISO 11925-2 [66]; (b) scheme of small flame test, EN ISO 11925-2 (sample size  $0.09 \times 0.25 \text{ m}^2$ ) [62,66]; (c) demonstration of the experiment on a sample of SMR + HRP (retardant) in 30 s.

The sample was fixed in the sample holder, and the holder was placed in the test chamber in a horizontal position. The combustion source was a small propane gas burner (Figure 3c). The height of the test flame was 20 mm. The burner was adjusted to an inclined position at an angle of  $45^\circ$ . The test started the moment the burner was pressed against the sample surface. The time of the experiment was set at 30 s. After 30 s, the burner was moved away and the processes of ignition, spontaneous combustion, falling off, or dripping of the sample were observed.



**Figure 3.** (a) Prepared experiment; (b) experiment at 10 s; (c) close-up of flame–sample contact at 20 s.

The experimental data to monitor the behaviour of the samples exposed to flame for 30 s included the mass loss and the flame spread over the surface during the experiment.

The experiments were carried out in two steps:

1st step: monitoring the effectiveness of the HRP-retardation coating applied to the wood samples.

2nd step: monitoring the effectiveness of the HRP-retardation coating on wood samples previously treated with fungicidal coatings (FUN, BOCHFUN, BOCH, NAP, and AQUQ).

The evaluation of the experiment focuses on the following:

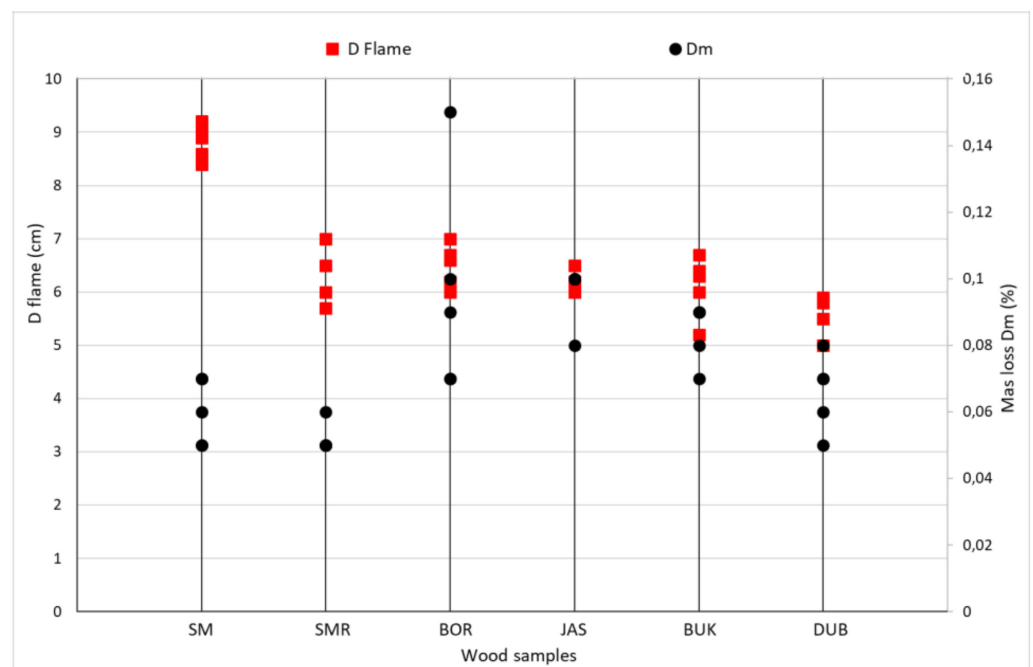
- Evaluation of the effectiveness of the fire-retardant coating on the selected wood samples. A significant dependence of the mass loss during the experiment and flame spread within 30 s on the wood species were determined using the QtiPlot software program (QtiPlot 0.8.5 in the GNU/Linux OS environment of the UBUNTU 6.06 distribution, Bucuresti, Romania) [67].
- Evaluation of the influence of the fungicidal coating on the retarder effectiveness and search for the optimal fungicidal coating as an undercoat for the selected retardant, again, based on the mass loss during the experiment and flame spread within 30 s.

### 3. Results and Discussion

This section may be divided by subheadings. It should provide a concise and precise description of the experimental results, their interpretation, as well as the experimental conclusions that can be drawn.

#### 3.1. Monitoring the Effectiveness of the HRP Retardant on Wood Samples

All samples exposed to flame for 30 s were ignited. The resulting flame reached a maximum height of 8.82 cm for spruce (Figure 4). The monitoring of mass loss was conducted by observing the mass change of the sample at the beginning and the end of the experiment. The experiments were short in time (30 s), with corresponding mass loss values (Figure 4). The assumptions of 100% efficiency and complete protection could not be confirmed. The mass changes were symbolic (Table 3) and smaller compared to the mass change of untreated samples. At the same time, the generated flames caused degradation of the sample surface which resulted in surface charring, as reported in [53,68,69]. Samples of different wood species demonstrated the variation of flame spread values (Table 4 and Figure 4). These values were confirmed by one-way ANOVA, which determined a significant dependence of flame spread on wood species (Table 3).



**Figure 4.** Dependence of mass change after application of a small flame initiator for 30 s and comparison of flame height for each wood sample.

**Table 3.** One-way ANOVA analysis of the dependence of mass loss and flame spread on tree species.

Sample	N	Mean	Standard Deviation	Variance	Standard Error
Table 1_2	30	0.07566666667	0.02269487764	0.000515057471	0.004143498808
Table 1_3	30	6.61	1.12505938541	1.26575862069	0.205406801307
Source	DF	Sum of Squares	Mean Square	F Value	p Value
Model	1	640.462681667	640.4622681667	1011.570709733	$2.100791912 \times 10^3$
Error	58	36.72193667	0.633136839081		
Total	59	677.184618333			

Null hypothesis: the means of all selected datasets are equal. Alternative hypothesis: the means of one or more selected datasets are different.

**Table 4.** Mass change of selected treated wood samples after 30 s of flame exposure.

Name	Untreated (%)	FUN (%)	BOCH FUN (%)	BOCH (%)	NAP (%)	AQUA (%)
SM	$0.06 \pm 0.0132$	$0.048 \pm 0.0132$	$0.038 \pm 0.0263$	$0.058 \pm 0.0172$	$0.042 \pm 0.0116$	$0.066 \pm 0.0089$
SMR	$0.05 \pm 0.004$	$0.04 \pm 0.0109$	$0.052 \pm 0.0248$	$0.05 \pm 0.0063$	$0.051 \pm 0.0116$	$0.058 \pm 0.0074$
BOR	$0.097 \pm 0.029$	$0.048 \pm 0.004$	$0.048 \pm 0.004$	$0.059 \pm 0.023$	$0.082 \pm 0.016$	$0.064 \pm 0.010$
JAS	$0.096 \pm 0.008$	$0.085 \pm 0.012$	$0.088 \pm 0.018$	$0.078 \pm 0.007$	$0.092 \pm 0.016$	$0.088 \pm 0.009$
BUK	$0.084 \pm 0.008$	$0.062 \pm 0.014$	$0.056 \pm 0.018$	$0.068 \pm 0.011$	$0.082 \pm 0.007$	$0.072 \pm 0.008$
DUB	$0.066 \pm 0.010$	$0.046 \pm 0.004$	$0.054 \pm 0.008$	$0.056 \pm 0.014$	$0.07 \pm 0.022$	$0.058 \pm 0.021$

HolzProf producers [53,69] present the efficiency of HolzProf (HRP) fire retardant as very high. Their tests with video, performed in internationally well-known accredited laboratories and certification centres, meet the classifications of fireproof efficiency Euro-class B-s1-d0, (UK class 0) on solid wood, according to EN 13501-1 [63]. However, the effect of other coatings has not been investigated. HRP was used as a protective coating on insulating panels made of recycled technical textiles. Danihelová et al. [70] also determined that the fire-technical properties complied with EN ISO 11925-2 [66]. The results obtained present a mass loss of more than 10% and place the material in reaction to fire class E [63]. Phromsaen et al. [71] conducted research on the effect of a selected concentration of diammonium phosphate ( $\geq 98\%$  purity) on wood. Based on the results of their study, wood samples impregnated with 30%wt of DAP can be classified as self-extinguishing materials and could meet the requirement for nonflammability in construction. However, their results were based on heat loading.

### 3.2. Monitoring the Effect of Selected Fungicidal Coatings on the Effectiveness of HRP

The coating, Ferric phosphate-based HRP, reduced mass loss during heat loading of the wood surface (Figure 4). The requirements for wood products also specify the biodegradation of wood, so further research was focused on the effect of the combination of protective coatings (Table 4). Fungicide products were selected on the basis of their practical application. The procedure for treating wooden elements with fungicidal coatings was designed according to the manufacturers' requirements. The subsequent HRP surface treatment should increase the thermal stability of the samples (Figure 5). The results obtained (Table 4) demonstrate a reduction in the mass loss of the samples compared to a simple HRP treatment only.

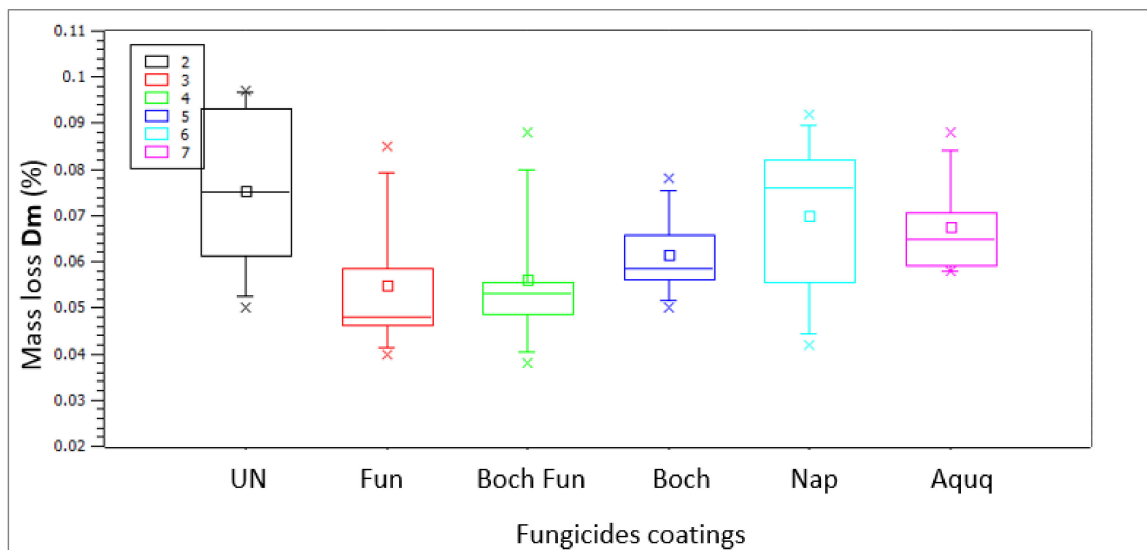




**Figure 5.** Presentation of wood samples after the experiment. The order of wood species is sorted from left to right as follows: 1 row—SM (spruce) and SMR (red spruce); 2 row—JAS (ash) and BOR (pine); 3 row—DUB (oak) and BUK (beech).

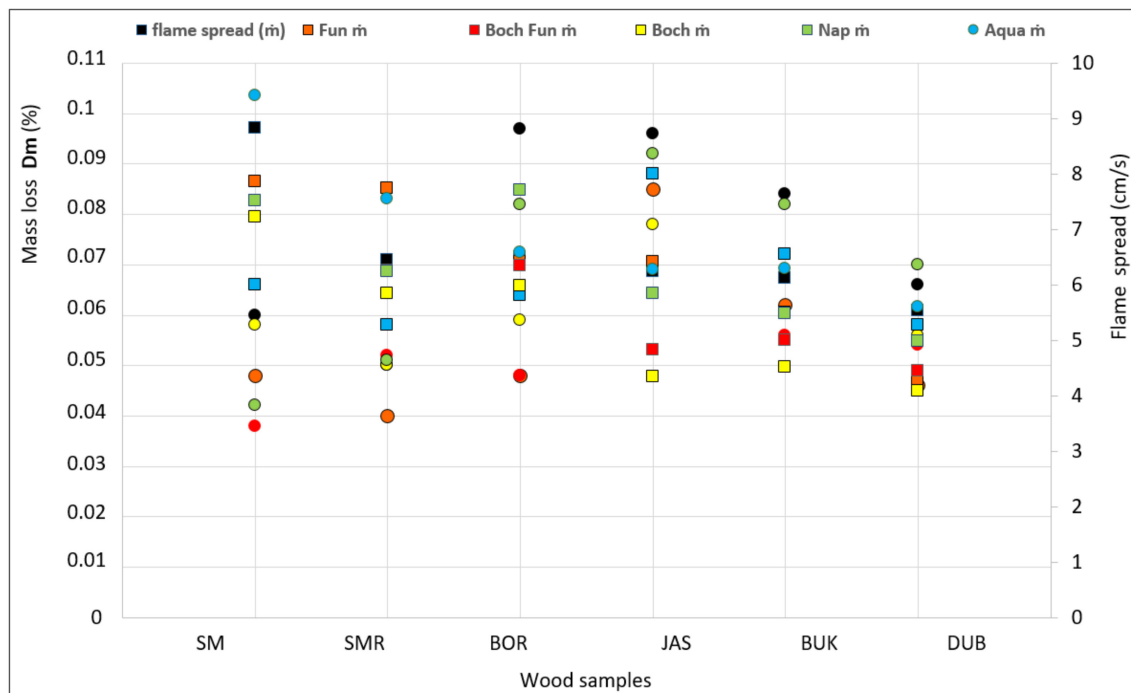
The experimental results were used to search for a significant dependence of the effect of fungicidal coatings on the retardant effectiveness. The variability of the obtained results was monitored by the QtiPlot software program [67]. The boxplot (Figure 6) indicated the variance of the mass-loss results in terms of fungicide-coating application. Boxplot 2 presents the mass loss of untreated samples by coatings, where the data are the highest (Table 4) and most scattered. It results from the variation in the type of wood samples specified in Figure 4. At the same time, the highest proportion of mass loss is observed for the untreated samples relative to the samples treated with fungicide coating. Based on the results, the influence of fungicidal coatings on the effectiveness of flame retardant can be accepted.

Another large scatter of results can be seen in boxplot 6 (Figure 6), which presents the fungicide coating NAP (glucose and alcohol-based). A stable effect can be observed with the fungicidal coating BOCH, i.e., boxplot 4, where the mass-loss values are virtually identical. The FUN coating (boxplot 3, Figure 6) is comparable to the above results. Both coatings have N-(3-aminopropyl)-N-dodecylpropane-1,3-diamine as the active ingredient. In terms of coating efficacy, regardless of the species, FUN has the most satisfactory result. Its mass-loss values are the lowest.



**Figure 6.** Boxplot of the variance of mass loss for individual fungicide coatings. Legend: UN—untreated with fungicide coating, 2—untreated with fungicide coating, 3—Fun (red), 4—Boch Fun (green), 5—Boch (dark blue), 6—Nap (light blue), 7—Aqua (violet).

A comparison of the mass losses with respect to the species (Figure 7) produces comparable results in terms of percent loss (0.04–0.09%). JAS wood can be considered the weakest wood sample where we observed the highest mass loss (Figure 7), and the value of mass loss of all fungicide coating samples is in the range of 0.08–0.09%. Ash is generally considered excellent wood with a constant energy value for heating all types of appliances [72]. The softwoods spruce and pine demonstrate the highest variance in mass loss in terms of the impact of fungicide coatings.



**Figure 7.** Mass loss obtained by small flame test and comparison of flame spreads in 30 s.

The theoretical assumption of NAP and AQUA samples, based on their chemical composition, as weaker fungicidal coatings relative to the others was confirmed. BOCH FUN has the highest amount of active fungicidal ingredients (Table 2) and achieves the most satisfactory results in terms of mass loss. At the same time, BOCH FUN wood samples present shorter flame-spread values than the other samples (Table 5 and Figure 7). The BOCH coating achieves the lowest flame-spread values (Figure 8). BOCH and BOCH FUN share a common active fungicidal ingredient: alkyl/benzyl (C12–16) dimethylbenzyl ammonium chloride (Table 2). BOCH has an additional retardant boric acid added to its structure (Table 2). Boric acid is also used in fire retardants [73–76]. The presence of boric acid can enhance the retardant effect of HRP coating, manifested by slower flame spread (Figure 8). The aforementioned fact can also be seen in the boxplots that do not consider the influence of the wood species (Figure 8).

Table 5. Comparison of flame height.

Name	Untreated (cm)	FUN (cm)	BOCH FUN (cm)	BOCH (cm)	NAP (cm)	AQUA (cm)
SM	8.82 ± 0.285	7.86 ± 0.458	7.52 ± 0.664	7.22 ± 0.381	7.52 ± 0.664	9.42 ± 0.371
SMR	6.44 ± 0.523	7.74 ± 1.028	6.26 ± 0.488	5.84 ± 0.326	6.24 ± 0.431	7.56 ± 1.228
BOR	6.5 ± 0.357	6.42 ± 0.795	6.34 ± 0.649	5.98 ± 0.146	7.7 ± 0.200	6.58 ± 0.305
JAS	6.24 ± 0.2224	6.42 ± 0.389	4.82 ± 0.213	4.34 ± 0.12	5.84 ± 0.531	6.28 ± 0.231
BUK	6.12 ± 0.441	5.5 ± 0.340	5.0 ± 0.275	4.52 ± 0.411	5.48 ± 0.470	6.3 ± 0.340
DUB	5.54 ± 0.313	4.24 ± 0.402	4.44 ± 0.496	4.08 ± 0.386	4.98 ± 0.354	5.6 ± 0.485

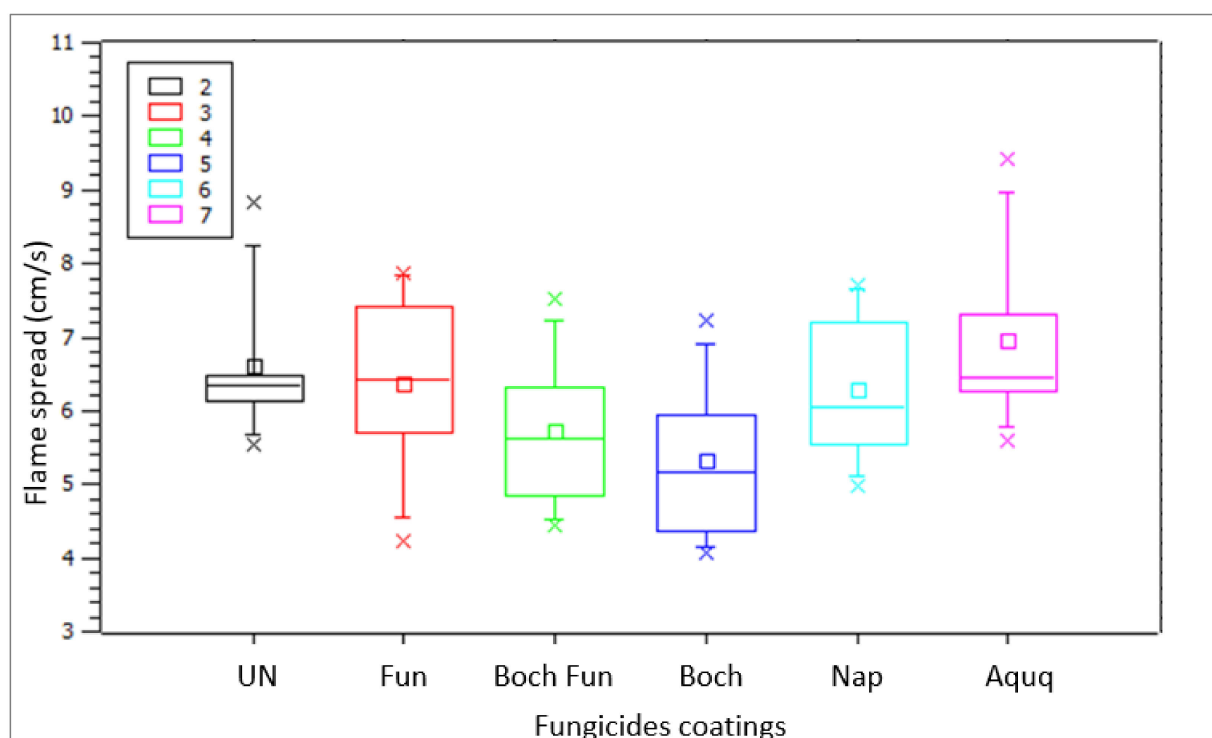


Figure 8. Boxplot to compare the flame spread for each fungicide coating. Legend: UN—untreated with fungicide coating, 2—untreated with fungicide coating, 3—Fun (red), 4—Boch Fun (green), 5—Boch (dark blue), 6—Nap (light blue), 7—Aqua (violet).

Oak, as our hardest wood species, maintains its dominant characteristic in thermal stability. It is difficult to ignite and demonstrates the lowest mass loss as well as flame spread regardless of the type of coating (Figure 8). Studies dealing with fuel wood suggest

this wood is a suitable fuel for boilers [77]. Vidholdova et al. [78] conducted experiments with thermally modified oak and fungicide coating. They confirmed the effect of thermally modified oak on increasing resistance to biological pests. This was also supported by the research of Gašpercová and Kozáková [79]. They performed experiments on pine and oak in identical conditions but used fungicide preparation LAZ with the same chemical composition as NAP and AQUA.

Osvald et al. [80] considered continuous mass loss measurement as the main evaluation criterion for retardant effectiveness. If a retardant indicated a mass loss of up to 5% within 60 s, it could be considered satisfactory. A mass loss of up to 5% represented the retardant decomposition and the wood did not burn. The second criterion was a total mass loss of up to 3 min. The experimental samples were beech and retardant coating, and the experiment time was 3 min. Our results, confronted with the requirements of [80], would meet the above criteria. However, extrapolation of the results from the 30 s to 60 s would not be possible because the mass loss for some samples with FUN and BOCH FUN coating would not reach 1%. The treated spruce samples demonstrate low values of mass loss, comparable to oak (Figure 7), but on the other hand, the highest values of flame spread (Figure 7). Mitrenga et al. [81] conducted research on the effectiveness of selected retardants applied to spruce samples. The samples were exposed to flame for 5 min. The selection of retardants was based on their composition (polyurethane—polyether polyol + nanosilica) and presented mass losses of 10%.

Chaouch et al. [82] performed a combination of surface treatment and thermal loading experiments in reverse order. First, the samples were thermally modified and then exposed to fungi. Heat treatment was performed on two softwood species (pine and silver fir) and three hardwood species (poplar, beech, and ash) at 230 °C under nitrogen for different times to reach mass losses of 5, 10, and 15%. Heat-treated samples were exposed to fungal decay using the brown rot fungus *Poria placenta*, and the mass losses due to fungal degradation were determined as well as the initial wood elemental composition.

The paper of Harangózo et al. [83] assessed the impact of the heat flux on the flammability of wood materials with the application of fire retardants potassium hydrogen carbonate ( $\text{KHCO}_3$ ) and azanium dihydrogen phosphate ( $\text{NH}_4\text{H}_2\text{PO}_4$ ), which can limit or slow down the wood combustion. After applying the fire retardants, the ignition time increased and, thus, confirmed the retardation effect.

#### 4. Conclusions

On the basis of the conducted experiments, the following conclusions were determined:

- Significant dependence of flame spread within 30 s on particular tree species can be confirmed.
- The oak samples indicated the most satisfactory results regarding the effect of flame retardant and the effect of the combination of fungicide coating and flame retardant.
- The evaluated retardants demonstrated different effects on the final values of mass loss and flame spread. The most satisfactory values, regardless of the underlying wood, were for the BOCH FUN sample. This sample had a chemical composition that combined several active ingredients Alkyl (C12–16) dimethylbenzyl ammonium chloride, N-(3aminopropyl)-N-dodecylpropane-1,3-diamine plus boric acid, a component of some flame retardants.

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