

Article

Evaluation of Fire Characteristics of Different Norway Spruce (*Picea abies*) Fractions in the Wood-Processing Industry

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Abstract

Wood-processing industrial facilities in which Norway spruce wood (*Picea abies*) is processed and where products such as sawdust, wood chips or wood are generated are considered high-risk operations from the perspective of fire safety and explosion hazards. This is due to the combination of combustible material, fine particulate matter, ignition sources, and the potential for dust explosions. In this article, we focused on three different fractions of spruce wood (*Picea abies*) commonly present in the wood-processing industry: sawdust, wood chips, and compact wood. Experimental measurements were carried out under laboratory conditions in accordance with ISO 871. Ignition temperature, flash-ignition temperature, and activation energy are key parameters that determine the susceptibility of spruce wood, sawdust, and wood dust to ignition. Fine wood fractions exhibit lower activation energy and lower ignition temperatures, which increases the probability of combustion initiation. The activation energy for spontaneous ignition of sawdust was $45.1 \text{ kJ}\cdot\text{mol}^{-1}$, compared with $66.5 \text{ kJ}\cdot\text{mol}^{-1}$ for compact wood and $31.9 \text{ kJ}\cdot\text{mol}^{-1}$ for wood chips. The activation energy for the flash point of sawdust was $48.5 \text{ kJ}\cdot\text{mol}^{-1}$, for wood chips was $36.8 \text{ kJ}\cdot\text{mol}^{-1}$ and for compact wood was $44.9 \text{ kJ}\cdot\text{mol}^{-1}$. In combination with airborne wood dust, these conditions create a significant potential for fire development and dust explosions in wood-processing industrial facilities.

Keywords: wood sawdust; wood chips; spruce wood; spontaneous ignition temperature; flash point temperature; activation energy; explosion

1. Introduction

From the perspective of materials science, wood is defined as a heterogeneous, anisotropic, and hygroscopic material of plant origin, characterized by a complex macroscopic and microscopic structure. It represents a complex system of substances with different physical and chemical properties [1]. According to [2] and [3], its advantages include easy workability, good thermal and acoustic insulation properties, environmental friendliness, the ability to damp vibrations, and a pleasing aesthetic appearance. In addition to these favourable properties, natural wood also has certain limitations that restrict the scope of its use. One of these limitations is its easy ignitability and combustibility. Understanding the fundamental principles of wood combustion is a primary prerequisite for predicting the risk of fire initiation and fire spread in industrial operations. The course of the thermo-oxidative reaction is influenced by numerous factors, which can be divided into primary and secondary factors. The primary factors include, in particular:



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- Anatomical properties: The wood species, whether hardwood or softwood, determines the degree of combustibility and the rate of burning of the wood material.
- Chemical composition: The proportion of the main components, namely cellulose, hemicelluloses, and lignin, directly determines the course of pyrolysis and the reactivity of the material. According to Osvald [4], wood species with a higher hemicellulose content are more combustible. As an example, it is possible to mention the lignin content depending on the wood species reported by [5]: Norway spruce (*Picea abies* K.) 26.9 wt.%, Scots pine (*Pinus sylvestris* L.) 26.6 wt.%, and European beech (*Fagus sylvatica* L.) 20.9 wt.%.
- Physical properties: A key role is played especially by current moisture content, porosity, diffusion, sorption, thermal conductivity, and specific heat capacity, all of which influence the rate of heat transfer into the wood structure. The moisture content of wood increases its resistance to ignition, since part of the supplied energy is consumed for the evaporation of free water, the disruption of bonds, and the evaporation of bound and chemically bound water. Water vapour also dilutes combustible gases, thereby reducing their ignitability. Wood does not contain free electrons in its structure and has high porosity, which makes it a poor conductor of heat [1].
- Wood structure: Combustibility is affected by the size of the openings of micro- and macro-capillaries, which influence the transport of oxygen into the wood material and the release of volatile products from the wood. As stated by Osvald [4], in addition to these physical properties, wood density is also important during combustion, since a denser material requires more energy for ignition and burning.
- Mechanical properties: The occurrence of cracks and fissures reduces the integrity of the material [6,7], thereby facilitating heat transfer through the material and accelerating its degradation.
- Fire-retardant protection: As stated by Mitrenga et al. [8], the application of flame retardants chemically or physically slows down the process of ignition and flame spread over the surface of a combustible material.
- Secondary factors are the environmental conditions under which the material burns and include the following:
 - Type and intensity of heat exposure to the material surface: The quality of the material's surface treatment is also significant. A well-finished surface reflects the energy of the heat source, thereby increasing the time required for ignition [1].
 - Oxygen concentration in the air: This factor determines the limiting oxygen concentration values at which the material is still capable of burning. According to Košík [9], the limiting oxygen index for spruce wood is 25.0 vol.%.
 - Geometry of the material, including its dimensions and degree of fragmentation: The more fragmented the material is, for example, in the form of solid wood pieces, shavings, or sawdust, the lower the energy required for its initiation [10].

Norway spruce (*Picea abies*) constitutes a substantial proportion of forest stands in Central Europe. Figure 1 shows the share of the main tree species in Europe's timber stock in 2025. Pine accounts for the largest share, at 26.3% of the total stock, followed by spruce at 20.4%. Beech (13.3%) and oak (10.8%) also have significant shares. Fir (5.4%) and birch (5.3%) have lower shares. Other tree species, which are not listed separately in the graph, together account for 18.5%. The graph shows that, in terms of timber stock, European forests are dominated by coniferous species, particularly pine and spruce, which together account for nearly half of the total timber stock.

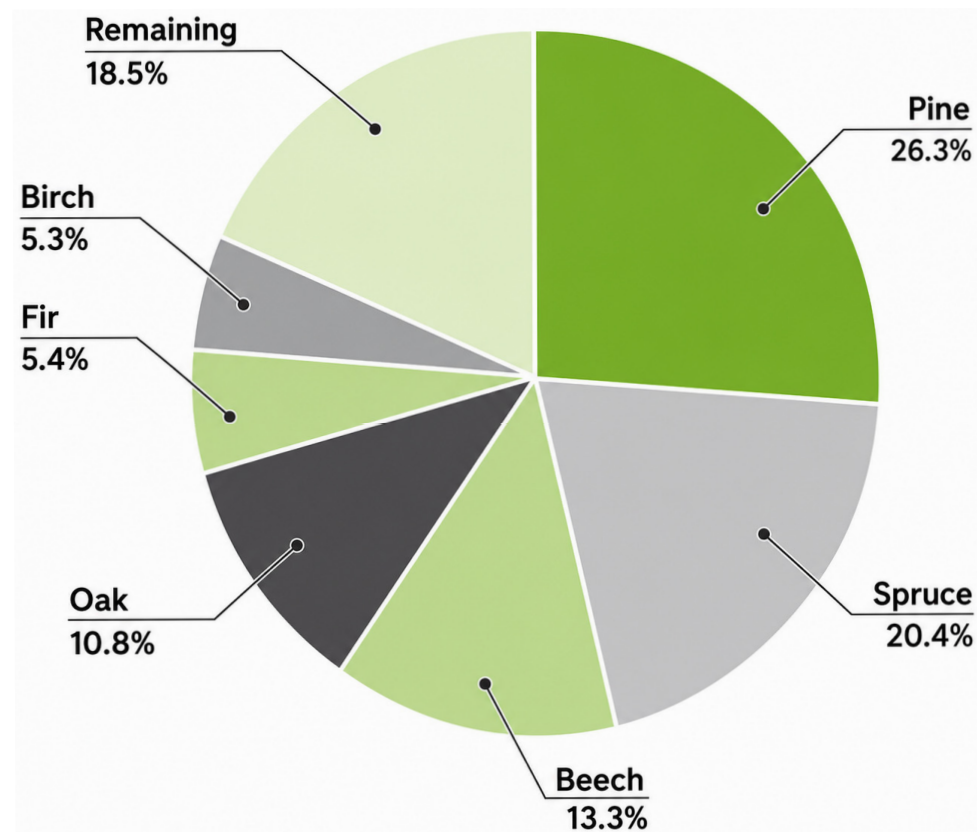


Figure 1. The main tree species in Europe's [11].

Due to its rapid growth, easy workability, and versatile use of biomass, Norway spruce is considered one of the important commercial wood species. Spruce wood is light in colour, ranging from whitish to yellowish, soft, elastic, and has a relatively low density of approximately $430\text{--}470\text{ kg/m}^3$ at 12% moisture content [12]. According to Fengel [13], the content of its main components is as follows: cellulose 40.4 wt.%, hemicelluloses 31.1 wt.%, and lignin 28.0 wt.%. Its use is particularly widespread in construction, including load-bearing structures, roof trusses, windows, doors, and flooring; in furniture production, including solid wood furniture, veneers, and interior cladding; as well as in the sawmilling, chemical, paper, and energy industries [14].

The forestry and wood-processing sector represents an important part of the European economy, and wood production constitutes a strategic raw material for both domestic and foreign markets. Within the European Union, the main producers of roundwood are primarily the countries of Northern and Central Europe (Figure 2). According to Eurostat [15], most of the roundwood harvested in the EU in 2022 was used as industrial wood, particularly for the production of sawn-wood, veneers, pulp, and paper. One quarter of the production was intended for use as fuelwood. In 2023, the largest producers of roundwood within the EU were Germany, Sweden, Finland, France, and Poland. According to Eurostat [16], these countries together accounted for 64% of the total production of roundwood in the EU.

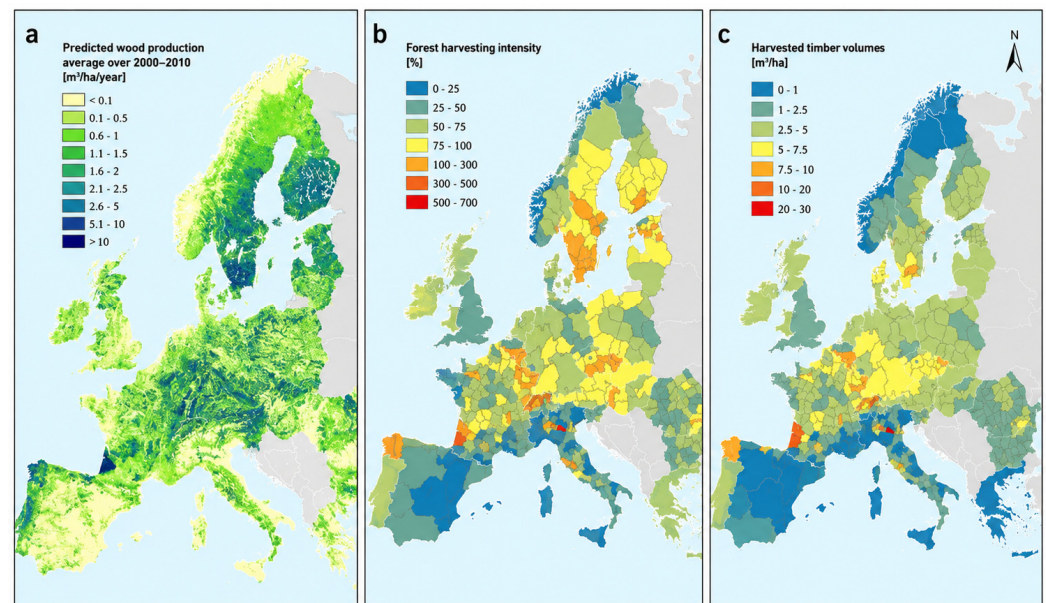


Figure 2. Wood production in European forests [17]; (a) predicted wood production in Europe, average over the period 2000–2010; (b) average forest harvesting intensity; (c) average harvested timber volumes from 2000–2010 in European administrative units.

From the perspective of the forestry and wood-processing industry, the ability of countries to further process wood is of particular importance. Grzegorzewska [18] emphasize that the competitiveness of the wood-processing industry depends not only on the availability of raw material, but also on the technological level of processing, labour productivity, and links to downstream sectors. Within the EU, the economically most significant countries in this field can be considered Sweden, France, Finland, and Germany, which in 2019 achieved a gross value added exceeding EUR 4 billion [19]. The Nordic countries, particularly Sweden and Finland, dominate in the processing of softwood, the production of pulp and paper, and the export of forestry products. In Slovakia, wood production has particular importance due to the country's high forest cover and the well-developed links between logging, primary processing, and related downstream sectors. According to Kánová et al. [20], the forestry and wood-processing sector accounts for a 2.61% share of GDP in Slovakia, which is above the average of European regions. The dominant activities include sawmill processing, plywood production, furniture manufacturing, and the paper industry. The Slovak Republic ranks among the European countries with the highest forest cover. Forests account for the largest area throughout the entire period under review, remaining at approximately 2,023,051 ha, of which production forests represent 73%, protective forests 17%, and special-purpose forests 10%. In Slovakia, coniferous and predominantly coniferous forests account for 26%, mixed forests for 20%, and broadleaved and predominantly broadleaved forests for 54%. Arable land represents the second-largest category, with an area of approximately 1.4 million hectares. Figure 3 shows that forest land has long dominated in Slovakia, while the area of agriculturally used land, particularly arable land and grassland, is decreasing slightly. This development points to gradual changes in land use patterns in favour of forest areas.

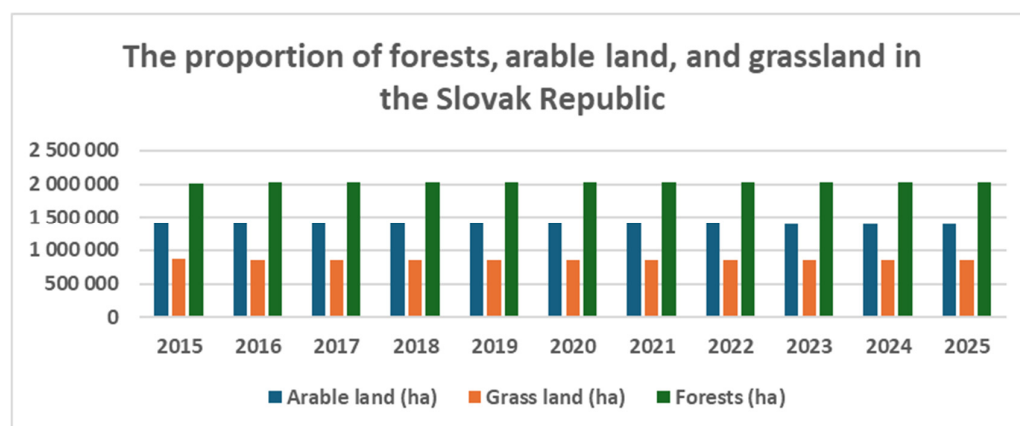


Figure 3. The proportion of forests, arable land and grassland in the Slovak Republic during 2015–2025 [21].

As stated by Vandlíčková et al. [22], the wood-processing industry is considered a high-risk sector from the perspective of fire protection, primarily due to the processing of combustible material, namely wood, the generation of by-products such as dust and chips, and the presence of various ignition sources. The main fire safety risks in the wood-processing industry include a range of technological processes, such as grinding, sanding, and sawing of wood, which generate significant amounts of combustible dust. A critical factor is the fineness of particles produced during wood surface treatment, where up to 98% of the waste consists of particles smaller than 0.5 mm. Another risk factor is the frequent absence of an effective wood dust removal system or failures in extraction systems, which lead to the accumulation of dust in the workplace. Cutting, sanding, milling, and drilling generate sparks, while rotating machinery creates hot surfaces, thereby increasing the risk of ignition or the formation of an explosive mixture after dust dispersion [23,24]. An equally important factor is the storage of large volumes of wood or semi-finished products, which represents a high fire load. In addition to wood storage, drying chambers are also highly hazardous, as high temperatures and the presence of dried wood require strict control in order to prevent self-ignition.

The fire hazard associated with combustible dust may occur, especially in places where it forms continuous deposits, through which fire can spread rapidly. There is a close relationship between dust fires and dust explosions: local combustion may initiate an explosion and, conversely, an explosion is often followed by a subsequent fire involving the remaining unreacted dust. Exceptions include cases in which the explosion itself consumes all the oxygen in an enclosed space, resulting in the spontaneous extinguishment of the flame. Dispersed combustible dust represents a high risk of a rapid oxidative reaction with an explosive course. Under specific conditions, this process may escalate from an explosion to the stage of detonation.

Therefore, the analysis of fire-technical characteristics is essential for the design of effective explosion and fire protection measures. For this purpose, testing methods are used to determine the fire-technical properties of materials. It is important that each testing method simulates fire conditions as accurately as possible in order to reveal the behaviour of materials during fire exposure. Poor test quality may result in an objective assessment of materials being compromised. Such an inaccurate assessment may occur in both positive and negative directions. Therefore, the proposed evaluation criteria of the selected testing method must be as precise as possible. Although previous studies have investigated the ignition behaviour and activation energy of spruce wood in different forms, most of them focused either on spruce dust, compact wood, pellets, briquettes, or thermally modified wood [25–28]. Therefore, there is still limited information on the direct comparison of

sawdust, wood chips, and compact wood originating from the same tree species and tested under identical methodological conditions. The uniqueness of the present study lies in the use of morphologically different but botanically homogeneous samples of Norway spruce (*Picea abies*), evaluated using a uniform experimental procedure. This approach enables a more objective assessment of the effect of material morphology on spontaneous ignition temperature, flashpoint temperature, ignition time, and activation energy.

2. Materials and Methods

The objects of investigation were three forms of spruce wood: spruce sawdust, spruce wood chips, and compact spruce wood. All samples originated from Norway spruce (*Picea abies*), which is among the most commonly used coniferous species in the wood-processing industry. Spruce wood is composed mainly of cellulose, hemicelluloses, and lignin, while also containing smaller amounts of resins and terpenes typical of coniferous wood (Table 1). From the perspective of fire safety, it is classified as a combustible organic material of Class A. Its behaviour under thermal exposure depends on several factors, particularly moisture content, bulk density, particle size, material structure, and the surface-area-to-volume ratio.

Table 1. Fire-technical characteristics of spruce wood (*Picea abies*) [1,29].

Fire-Technical Characteristic	Units	Value
Flash point temperature	°C	350–360
Spontaneous ignition temperature	°C	390–400
Smouldering temperature	°C	280–290
Oxygen index	%obj.	25
Heat of combustion	MJ.kg ^{−1}	19.45
Heating value	MJ.kg ^{−1}	17.2
Critical heat flux	kW.m ^{−2}	9.0

Spruce sawdust (Figure 4a) represented a fine-grained material generated as a by-product of the wood-processing industry. Owing to its high specific surface area, it may respond more rapidly to thermal exposure than materials with larger particle dimensions. Spruce wood chips (Figure 4b) represented a fragmented wood material with a larger particle fraction and a lower surface-area-to-volume ratio compared with sawdust. Compact spruce wood (Figure 4c) was included as a reference form of solid wood, for which a different course of heating, ignition, and subsequent combustion can be expected due to the higher integrity and compactness of the material.

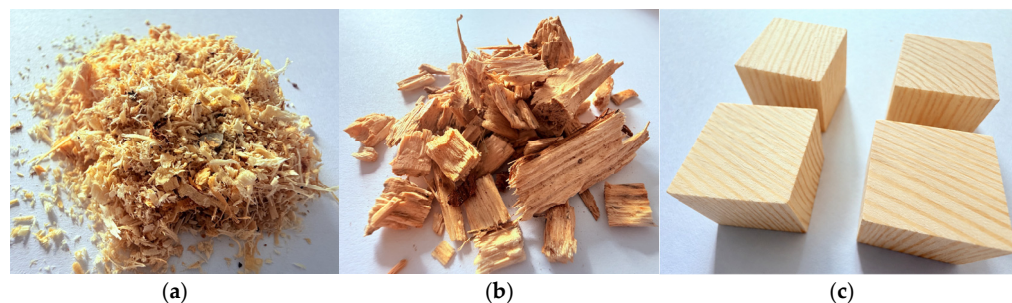


Figure 4. Sample of different fractions of spruce wood (*Picea abies*): (a) wood sawdust; (b) wood chips; (c) compact wood.

Prior to testing, the samples were conditioned in accordance with [30] at a temperature of 23 ± 2 °C and a relative humidity of $50 \pm 5\%$ for 40 h. The purpose of conditioning was to ensure comparable initial conditions for the individual samples and to minimize the influence of different initial moisture contents on the test results. Subsequently, the

basic parameters of the investigated samples, particularly their mass and moisture content, were determined. The mass of the samples used for determining the spontaneous ignition temperature and flash point temperature was 3.0 ± 0.2 g, in accordance with the methodological procedure according to the STN ISO 871 [31]. This procedure evaluates a general ignition response of solid combustible materials under controlled thermal exposure and has also been applied in previous studies on wood and biomass-based materials [25–28]. Therefore, ISO 871 was used in this study as an adapted, reproducible, and comparable methodological framework for testing different morphological forms of Norway spruce. The chemical composition of *Picea abies* samples was analyzed according to standardized TAPPI methods. Ash, extractives, cellulose, lignin, holocellulose and hemicellulose contents were determined. Samples measuring 2×2 cm were prepared for analysis, which were subsequently crushed for the needs of individual TAPPI methods (TAPPIT T 211, TAPPIT T 204, TAPPIT T 222). All analyses were performed in duplicate, and average values were used for evaluation.

The moisture content was determined gravimetrically based on the difference between the mass of the sample before drying and its mass after drying to a constant weight, according to the following equation:

$$W = \frac{m_1 - m_2}{m_1} \times 100 \quad (1)$$

where:

- * W—moisture content of the sample (%);
- * m_1 —mass of the sample before drying (g);
- * m_2 —mass of the sample after drying to a constant weight (g).

First, the spontaneous ignition temperature and flash point temperature were determined in accordance with [31]. The test procedure was based on identifying the lowest furnace temperature at which ignition of the investigated material occurred. The tests were performed in a hot-air furnace (Figure 5). For the determination of the flash point temperature, the sample was exposed to an ignition flame, whereas the spontaneous ignition temperature was determined without the use of an ignition flame. The temperature during the experiment was recorded using a Pico Technology USB TC-08 (Pico Technology Ltd., St Neots, United Kingdom) data logger.

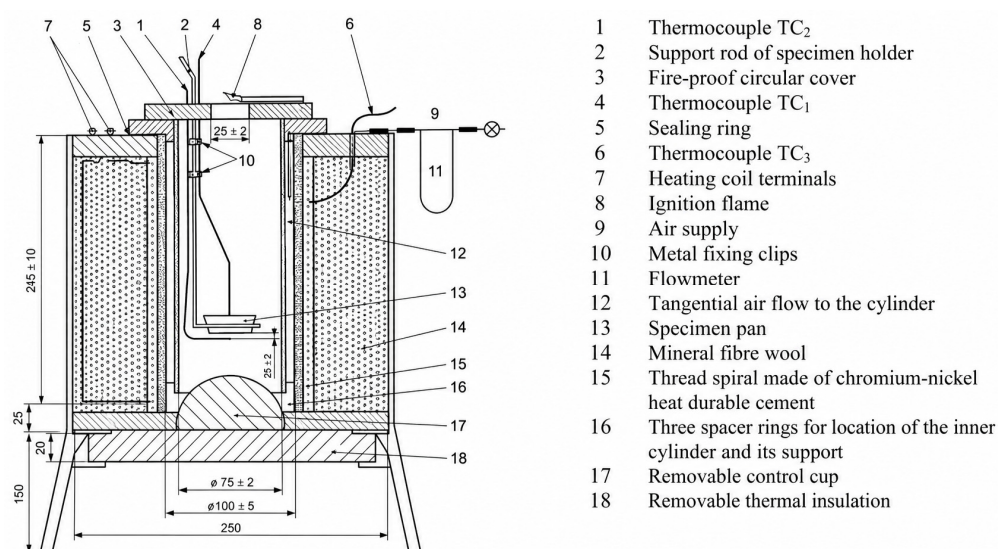


Figure 5. Scheme of hot-air furnace [31].

The sample was placed in the hot-air furnace and observed for 10 min. After the observation interval, the temperature was increased or decreased by 50 °C, depending on whether ignition of the sample occurred. Each measurement was performed using a new material sample. After the temperature range had been established, the test was initiated at a temperature 10 °C lower than the highest temperature within the determined range. Subsequently, the temperature was gradually reduced by 10 °C until reaching the temperature at which the sample did not ignite within 10 min. The same procedure was applied for determining both the spontaneous ignition temperature and the flash point temperature. The spontaneous ignition temperature was recorded as the lowest temperature at which ignition or glowing of the sample occurred without the use of an ignition flame. The flash point temperature was recorded as the lowest temperature at which ignition of the sample occurred during the 10-min interval in the presence of an ignition flame [31].

The methodological approach applied in this study was based on the Setchkin furnace test and followed the thermoanalytical procedures published by Martinka et al. [25] and Zachar et al. [26]. After determining the minimum spontaneous ignition temperature and flash point temperature, the furnace temperature was gradually increased by 10, 20, 30, 40, 50, 60, 70, 80, 90, and 100 °C above the determined minimum value. At each set temperature, the ignition time of the sample was recorded. Each test was repeated three times, and the resulting ignition temperature and ignition time values were expressed as average values.

The obtained data were subsequently used to evaluate the relationship between the ignition time and the reciprocal value of the thermodynamic temperature. This relationship was expressed by an exponential equation developed in Microsoft Excel. Based on the measured values, the activation energy was calculated according to the equation published by Semenov [32], which represents an analogy to the Arrhenius equation describing the temperature dependence of the ignition process:

$$E = \ln \left(\frac{t}{A} \right) \times R \times T \quad (2)$$

where E represents the activation energy ($\text{J} \cdot \text{mol}^{-1}$), t is the ignition time (s), A is the pre-exponential factor (-), R is the universal gas constant with a value of $8.314 \text{ J} \cdot \text{K}^{-1} \cdot \text{mol}^{-1}$, and T is the thermodynamic ignition temperature (K). The values of the pre-exponential factor were derived from the exponential equation describing the dependence of ignition time on thermodynamic temperature. The equation was expressed in the form:

$$t = A e^{B(1/T)} \quad (3)$$

where t is the ignition time (s), T is the thermodynamic ignition temperature (K), A is the coefficient preceding the exponential term, and B is the exponential regression coefficient. The value of A was obtained from the exponential regression equation as the initial value of the function y . The activation energy was subsequently used as a comparative parameter for assessing the susceptibility of the individual forms of spruce wood to ignition.

The experimental procedure designed in this way enables comparison of the fire-technical behaviour of spruce wood in different material forms. It is assumed that differences among sawdust, wood chips, and compact wood will be reflected mainly in the values of spontaneous ignition temperature, flash point temperature, and ignition time, since the individual material forms differ in particle size, surface area available for oxidation, compactness, and heat accumulation capacity.

3. Results and Discussion

By means of experimental measurements under laboratory conditions, the spontaneous ignition temperature and flashpoint temperature of spruce wood samples were determined in accordance with [31]. Different fractions of spruce wood used in the wood-processing industry, namely wood sawdust, wood chips, and compact wood, were analyzed, and their explosion risk was assessed. The measurements were based on the reported spontaneous ignition and flashpoint temperatures of spruce wood listed in the Catalogue of Fire-Technical Properties of Materials Reports, Slovak Republic. The Catalogue states that the spontaneous ignition temperature ranges from 390 to 400 °C and the flashpoint temperature from 350 to 360 °C [33].

The chemical analysis of the *Picea abies* sample demonstrated a typical composition of softwood, characterized by a dominant proportion of polysaccharide components and a relatively low content of inorganic substances (Table 2). Holocellulose represented the highest proportion, accounting for 68.73%, and significantly influenced the thermal decomposition of wood. During wood heating, softwoods tend to produce a higher amount of true combustible gases, which contribute to the initiation of combustion. The cellulose content in the *Picea abies* sample reached an average value of 38.79%, while the hemicellulose content was 30.32%. The average lignin content was 26.96%, which corresponds to typical values for spruce wood. Lignin decomposes over a wider temperature range and therefore affects the course of combustion and the rate of flame spread. Extractives in the experimental *Picea abies* sample reached low values (Table 2). The ash content was also low, at 0.95%, indicating a high proportion of organic combustible components in the material.

Table 2. Determined chemical component of the *Picea abies* sample.

Chemical Component	Sample 1	Sample 2	Average	Standard Deviation
Ash (%)	0.9549	0.9528	0.9539	0.0015
Extractive substances acetone (%)	0.6855	0.6879	0.6867	0.0017
Extractive substances ethanol (%)	1.7641	1.7703	1.7672	0.0044
Extractive substances ethanol-toulene (%)	1.6766	1.6825	1.6795	0.0042
Cellulose (%)	39.4326	38.1440	38.78830	0.9112
Lignin (%)	26.6707	27.2481	26.9596	0.4086
Holocellulose (%)	68.7286	69.4791	69.1038	0.5306
Hemicellulose (%)	29.2960	31.3351	30.3155	1.4419

Prior to measurement, the samples were conditioned in accordance with [26] (Table 3). The lowest moisture content was recorded in wood chips (5.80%), while the highest was measured in compact wood (7.45%). All investigated fractions of spruce wood exhibited a standard moisture content typical of technically dried wood used in wood-processing practice, as reported in the relevant literature [34–36].

The moisture content of wood depends on its intended use. Several sources report 8–12% as the target moisture content for technical drying, particularly for joinery or interior applications. For certain structural construction products, the recommended moisture content is 12–15%, while for energy use, the recommended moisture content ranges from 10 to 20%.

Table 3. Moisture content of the sample for the experimental fractions of spruce wood.

Sample	Mass Before Drying (g)	Oven-Dry-Mass (g)	Moisture Content (%)
Wood sawdust	5.00	4.59	8.20
Wood chips	5.00	4.71	5.80
Compact wood	5.00	4.65	7.00

The spontaneous ignition temperature of wood sawdust was experimentally determined to be 443 °C, while the temperature of the hot-air furnace was 440 °C. Thermal decomposition occurred after 228 s, and the process was characterized by homogeneous combustion accompanied by flame formation. At this temperature, a mass loss of 84.36% was recorded. The lowest spontaneous ignition temperature among all experimental samples was determined for the wood chip sample, namely 434 °C, at a hot-air furnace temperature of 420 °C. In this case as well, thermal decomposition was accompanied by homogeneous combustion with flame formation. At the same time, this sample exhibited the longest thermal decomposition time, reaching 319 s. The mass loss amounted to 82.00%. The compact wood sample showed a spontaneous ignition temperature of 447 °C, a value very close to that of the wood sawdust sample, while the hot-air furnace temperature was also 440 °C. During the experiment, homogeneous combustion accompanied by flame formation was also observed for this sample. Compared with the wood sawdust sample, thermal decomposition occurred later, specifically after 275 s. The mass loss at the given temperature was 83.00%. Figure 6 illustrates the spontaneous ignition process for all samples.

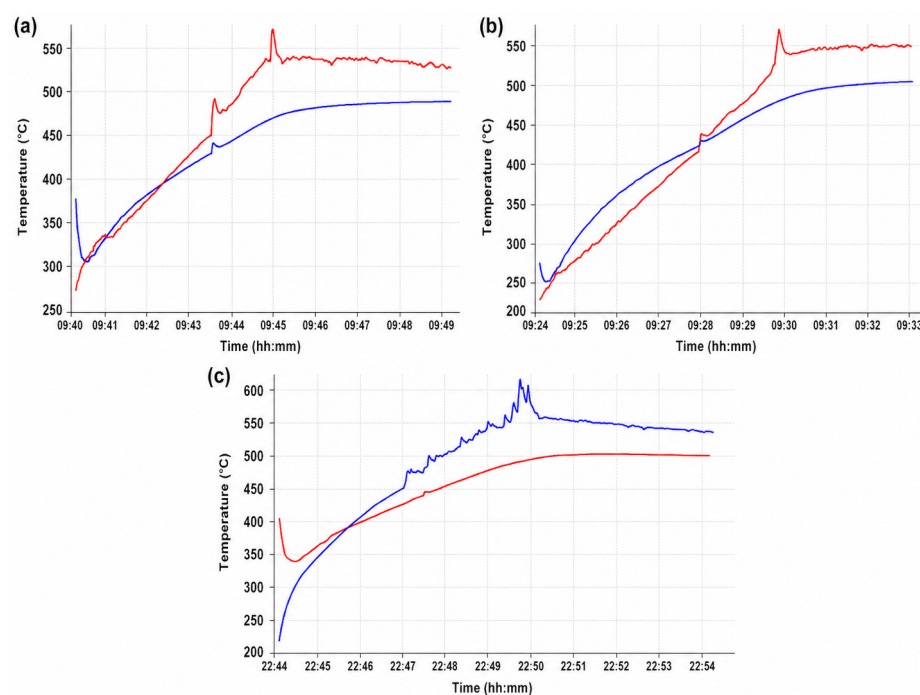


Figure 6. The spontaneous ignition process of the sample (*Picea abies*). (a) sawdust (temperature 440 °C); (b) wood chips (temperature 460 °C); (c) compact wood (temperature 440 °C). Legend: blue line = temperature about the sample, red line = temperature under the sample. *x*-axis = time, *y*-axis = temperature.

The flashpoint temperature of wood sawdust was experimentally determined to be 314 °C at a hot-air furnace temperature of 310 °C. This was the lowest flashpoint temperature recorded among all tested samples. Thermal decomposition occurred after 565 s, while white smoke was observed at 450 s before the actual flash ignition of the sample. During the flash ignition of the wood sawdust sample, homogeneous combustion accompanied by flame formation was observed. The mass loss was 74.25%. The wood chip sample reached a flashpoint temperature of 330 °C, while the sample temperature was 343 °C. Homogeneous combustion with flame formation was also observed for this sample. Thermal decomposition occurred within the induction period after 461 s, which represented the shortest time among the experimental samples. The mass loss at the given temperature

reached 70.00%. The highest flashpoint temperature was determined for the compact wood sample, namely 340 °C. All experimental samples exhibited lower flashpoint temperatures than those reported in the [35]. In the compact wood sample, thermal decomposition occurred after 473 s, and the recorded mass loss was 72.87%. Figure 7 illustrates the flashpoint process for all samples.

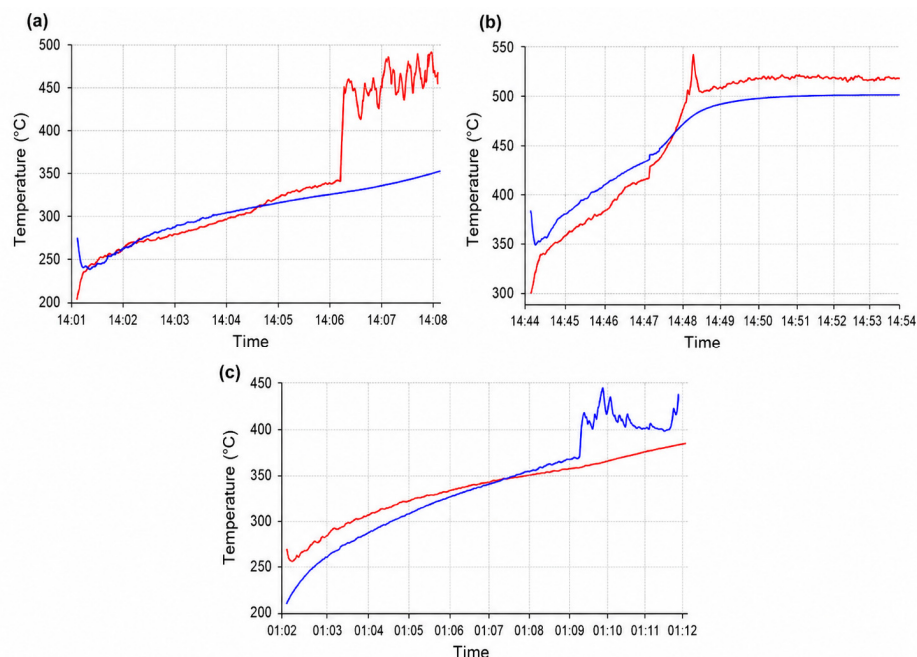


Figure 7. The flash point process of the sample (*Picea abies*). (a) sawdust (temperature 320 °C); (b) wood chips (temperature 340 °C); (c) compact wood (temperature 340 °C). Legend: blue line = temperature about the sample, red line = temperature under the sample. *x*-axis = time, *y*-axis = temperature.

Table 4 shows the measurement data for the experimental samples (wood sawdust, chips of wood, compact wood).

Table 4. Spontaneous ignition temperature, flashpoint temperature and mass loss for the experimental sample.

Sample	Wood Sawdust	Wood Chips	Compact Wood
Spontaneous ignition temperature (°C)	440 ± 2	420 ± 2	440 ± 2
Induction period (s)	228 ± 3	319 ± 4	275 ± 3
Mass loss(%)	84.36 ± 0.26	82.00 ± 0.30	83.00 ± 0.20
Flashpoint temperature (°C)	310 ± 5	330 ± 5	340 ± 5
Induction period (s)	565 ± 5	461 ± 5	473 ± 5
Mass loss (%)	74.25 ± 0.25	70.00 ± 0.30	72.87 ± 0.25

For compact spruce wood, Zachar et al. [26] recorded a minimum flashpoint temperature of 355 °C and a minimum spontaneous ignition temperature of 429 °C. Within their measurements, the spontaneous ignition temperature ranged from 429 to 472 °C, while the flashpoint temperature ranged from 355 to 418 °C. The results measured in our study fall within the temperature range reported by these authors. The spontaneous ignition temperature of spruce wood sawdust was investigated by Tureková [37]. Using a different measurement method, namely spontaneous ignition on a hot surface, they determined a lower temperature of 300 °C. Mračková et al. [27] tested various fractions of spruce sawdust in terms of their fire-technical properties. Depending on the spruce sawdust fraction, they determined the spontaneous ignition temperature to be 350–360 °C,

which is substantially lower than the values obtained in our measurements. The values of spontaneous ignition temperature and flashpoint temperature measured for compact spruce wood in our study are consistent with the literature [1,29,38,39]. We agree with the opinion of Mračková et al. [28] that, in heterogeneous spruce wood samples, such as sawdust or chips, material compaction, higher density, and finer material fractions increase resistance to combustion initiation.

In accordance with the Setchkin furnace test used by Martinka et al. [25] and Zachar et al. [26], an exponential curve was constructed, the correlation coefficient was determined, and the activation energy was calculated for each investigated sample separately for the spontaneous ignition temperature and flashpoint temperature. The value of A was therefore obtained directly from the regression equation displayed in Figures 8–13 (value of the y). Figure 8 shows the dependence of the induction period on the inverse value of the spontaneous ignition temperature for the wood sawdust sample of Norway spruce (*Picea abies*). The measured data indicate an increasing trend, where a decreasing spontaneous ignition temperature is associated with a longer induction period. The coefficient of determination ($R^2 = 0.4869$) confirms a low dependence between the monitored factors. The scatter of the data showed that the longest induction periods, exceeding 200 s, were recorded at higher values of $1/T$, confirming a slowdown in the processes leading to spontaneous ignition. The spontaneous ignition temperature of the wood sawdust sample was not affected solely by temperature, but also by other properties, including moisture content, particle size, sample heterogeneity, insufficient pressure during sample preparation, and the method of sample placement.

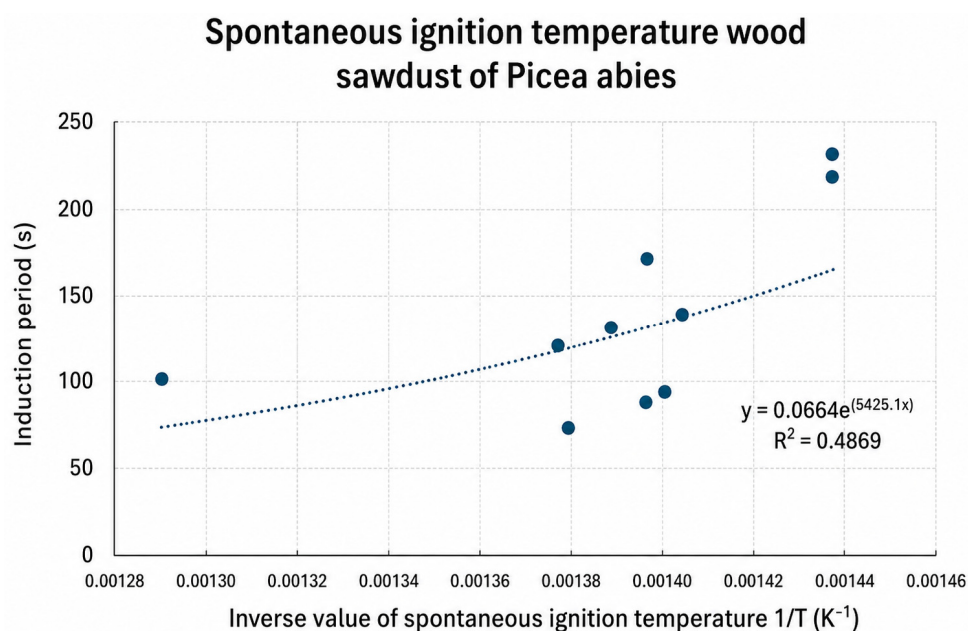


Figure 8. Dependency between the spontaneous ignition induction period and the inverse value of thermodynamic temperature of wood sawdust (*Picea abies*).

The flashpoint temperature exhibited a more linear exponential increase in the induction period with decreasing temperature (Figure 9), as evidenced by the lower scatter of the data. This trend indicates that, at lower temperatures, the wood sawdust sample is more stable, whereas after exceeding critical temperature values, a rapid acceleration of oxidative processes leading to flash ignition occurs. The induction periods were measured in the range of approximately 210 to 560 s, depending on the applied temperature. The coefficient of determination ($R^2 = 0.8334$) indicates a strong relationship between the inverse value of the flashpoint temperature and the induction period.

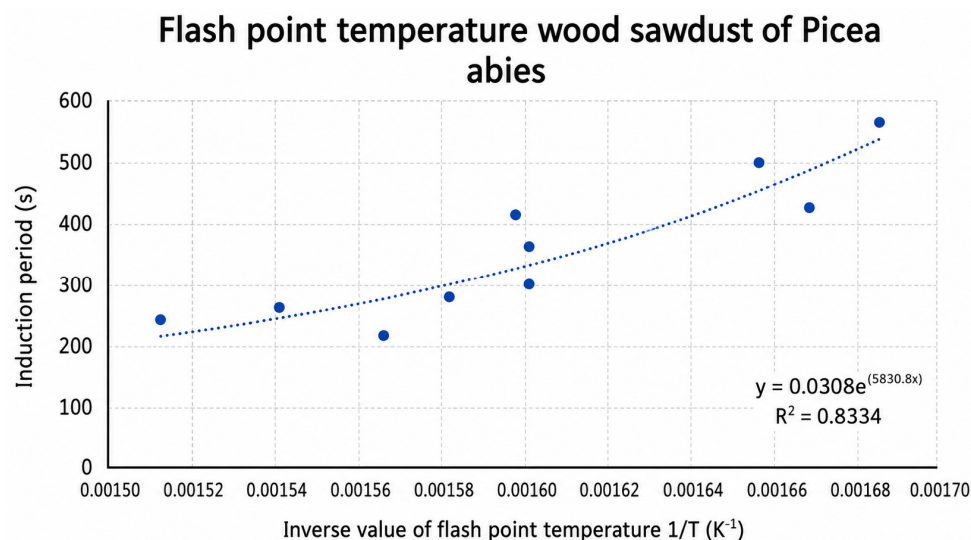


Figure 9. Dependency between the flashpoint induction period and the inverse value of thermodynamic temperature of wood sawdust (*Picea abies*).

Figure 10 illustrates the course of spontaneous ignition in the Setchkin furnace test for wood chips of Norway spruce (*Picea abies*). The results show an increasing trend, i.e., with an increasing value of $1/T$, which corresponds to a lower temperature, the induction period becomes longer. The scatter of the data is relatively pronounced, indicating that the length of the induction period was not influenced solely by temperature itself, but also by other material properties. In the case of wood chips, this scatter can be attributed mainly to sample heterogeneity, namely differences in particle size and shape, uneven material arrangement, varying porosity of the layer, and differences in moisture content. These factors may significantly affect the rate of heat accumulation and the course of thermo-oxidative processes, and consequently also the time required for spontaneous ignition to occur. The coefficient of determination ($R^2 = 0.4144$) indicates a moderate agreement between the model and the experimental data.

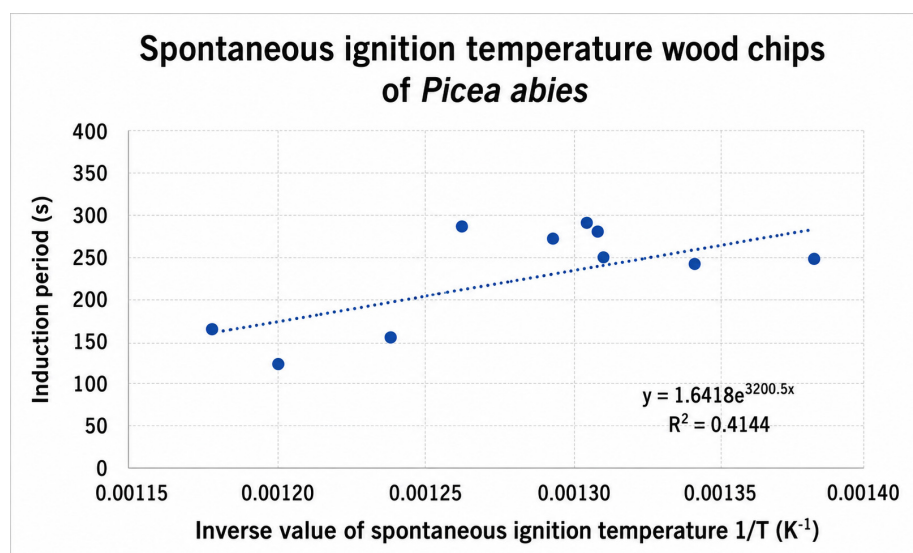


Figure 10. Dependency between the spontaneous ignition induction period and the inverse value of thermodynamic temperature of wood chips (*Picea abies*).

The flashpoint temperature of the wood chip sample exhibited a more stable course than the spontaneous ignition temperature (Figure 11). The measured values followed

the course of the exponential trend curve, indicating a stable and consistent character of the relationship. The exponential function describes the measured course very accurately, as confirmed by the high coefficient of determination ($R^2 = 0.9205$). Such a high level of agreement suggests that, in the case of wood chips, the induction period was predominantly influenced by temperature.

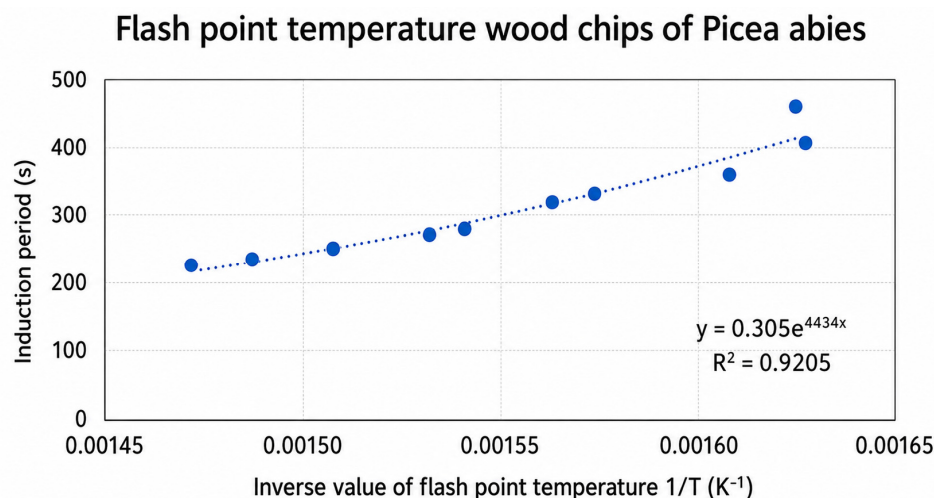


Figure 11. Dependency between the flashpoint induction period and the inverse value of thermodynamic temperature of wood chips (*Picea abies*).

The final investigated sample was the compact wood sample. The spontaneous ignition process (Figure 12) followed a relatively similar course to that observed for the wood sawdust and wood chip samples. In this case as well, a relatively pronounced scatter of data points was observed, indicating that the induction period was not influenced solely by temperature. For the compact wood sample, this variability may have been caused by the internal structure of the wood. Its behaviour during heating is influenced by fibre orientation, local density, resin content, moisture distribution, and possible microscopic cracks. The coefficient of determination ($R^2 = 0.5411$) indicates a moderately strong agreement.

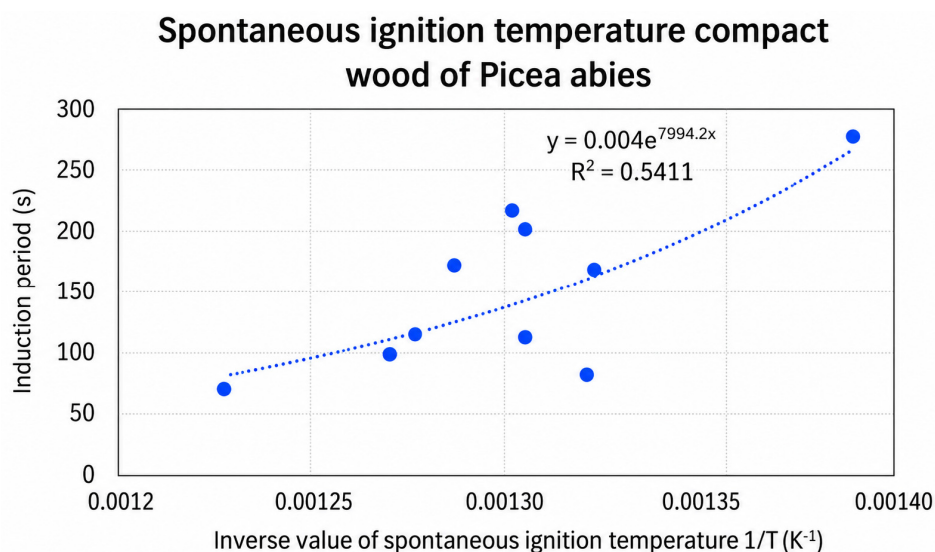


Figure 12. Dependency between the spontaneous ignition induction period and the inverse value of the thermodynamic temperature of compact wood (*Picea abies*).

The flashpoint temperature also exhibited a stable course for the compact wood sample, without a pronounced scatter of the measured data points (Figure 13). The results therefore

confirm that, in the compact spruce wood sample, the relationship between the inverse value of the flashpoint temperature and the length of the induction period is significant and can be well described by an exponential function, with temperature representing the dominant variable influencing the time required for flash ignition to occur. The exponential trendline describes the course of the data with a high level of agreement, as confirmed by the coefficient of determination ($R^2 = 0.8898$).

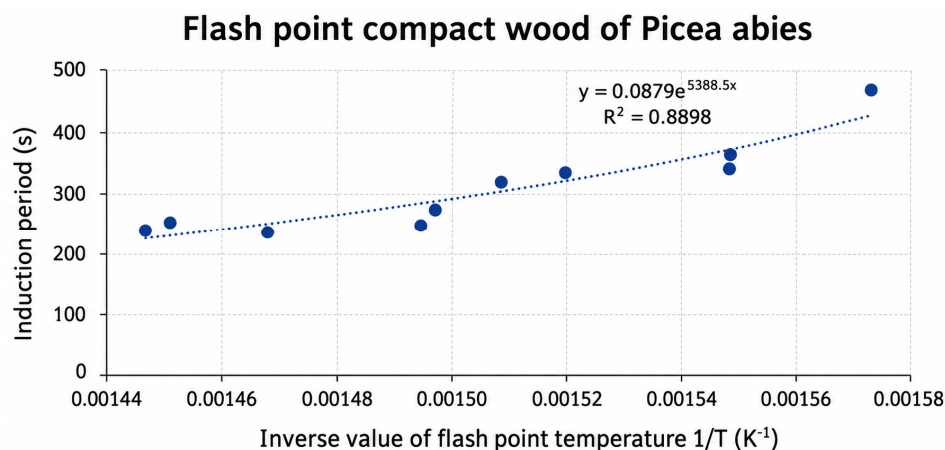


Figure 13. Dependency between the flashpoint ignition induction period and the inverse value of the thermodynamic temperature of compact wood (*Picea abies*).

Overall, it can be stated that higher model accuracy was demonstrated for the flash-point temperature in all spruce wood samples. The flash ignition process is more stable and less affected by material heterogeneity than the spontaneous ignition process. The most stable behaviour with respect to the induction period and temperature was observed for the wood chip sample, whereas the greatest scatter of data was recorded for the wood sawdust sample. Industrial operations where wood dust or sawdust is generated represent the highest risk, since under suitable conditions this material can overheat more rapidly. In the case of wood chips, the risk is associated mainly with storage in larger volumes, where heat dissipation may be limited and local overheating may occur. This creates conditions favourable for the process of spontaneous ignition. From the perspective of the investigated samples, compact wood represents a more stable form in terms of spontaneous ignition. However, under long-term thermal stress, gradual degradation and subsequent initiation of combustion may occur.

In accordance with the Arrhenius equation and the applied methodology, the activation energy was calculated for the experimental spruce wood samples, namely sawdust, chips, and compact wood. The results are presented in Table 5.

Table 5. Activation energy for the sample of spruce wood (*Picea abies*).

Sample	Activation Energy of Spontaneous Ignition (kJ.mol ⁻¹)	Activation Energy of Flash Point (kJ.mol ⁻¹)
Wood sawdust	45.1	48.5
Wood chips	31.9	36.8
Compact wood	66.5	44.9

When comparing the results with other studies, it can be stated that the spontaneous ignition temperature and flashpoint temperature depend on the structure of the wood material. Martinka et al. [25] report that the activation energy of spontaneous ignition of spruce wood was lowest for the dust form, at 44.1 kJ.mol⁻¹, higher for compact wood, at 48.1 kJ.mol⁻¹, and highest for pellets, at 59.0 kJ.mol⁻¹. In comparison with our results,

agreement was confirmed for the activation energy of spontaneous ignition of sawdust, which reached $45.1 \text{ kJ}\cdot\text{mol}^{-1}$. However, a substantially higher value was obtained for the compact wood sample, namely $66.5 \text{ kJ}\cdot\text{mol}^{-1}$. This value corresponds to the research by Zachar et al. [26], who calculated the activation energy of spontaneous ignition for compact wood as $67.15 \text{ kJ}\cdot\text{mol}^{-1}$. These differences may have been caused by the age of the wood, moisture content, or the calculation method. Comparable results with the cited study were also recorded for the activation energy of flash ignition of the compact wood sample. Zachar et al. [26] report a value of $39.09 \text{ kJ}\cdot\text{mol}^{-1}$, while the value calculated in our study was $44.9 \text{ kJ}\cdot\text{mol}^{-1}$. Literature data on the activation energy of spruce wood chips are limited, as most available studies focus on spruce dust, compact wood, pellets, briquettes, or Thermowood. The calculated activation energy of spontaneous ignition of wood chips, $31.9 \text{ kJ}\cdot\text{mol}^{-1}$, is lower than the values reported for spruce dust, compact wood, and pellets. Conversely, the activation energy of flash ignition of wood chips, $36.8 \text{ kJ}\cdot\text{mol}^{-1}$, is comparable with literature data for the flashpoint of spruce wood and Thermowood [25,26,40–42]. The lower values observed for wood chips may be related to their higher structural heterogeneity, different particle sizes, and variable heat and oxygen transfer within the tested sample. Overall, the results confirm that activation energy depends not only on the chemical composition of wood, but also significantly on its physical form, density, porosity, and the method of thermal loading.

4. Conclusions

The results indicate that, within wood-processing enterprises, spruce wood cannot be assessed as a uniform material; rather, it is necessary to distinguish its specific physical form. Wood sawdust, wood chips, and compact wood exhibit different susceptibility to thermal decomposition, flash ignition, and spontaneous ignition, which has direct implications for the safety of storage, handling, and technological processing.

Within the selected fire-technical characteristics investigated, the highest risk is associated in particular with fine particulate forms of wood, such as sawdust. Due to their structure and specific surface area, these materials are more prone to overheating and, under suitable conditions, may more rapidly form a combustible mixture with oxygen. In operations where wood dust or sawdust is generated, it is therefore essential to ensure effective extraction, regular removal of deposits, temperature control of technological equipment, and prevention of contact with hot surfaces or sparks.

Wood chips exhibited the lowest spontaneous ignition and flashpoint temperatures among the tested samples. The main problem arises especially during storage in larger volumes under insufficiently ventilated conditions, where, due to the structure of wood chips, heat accumulation, limited heat dissipation, and local overheating may occur. For this reason, it is important to control the height and volume of stored layers, the moisture content of the material, the aeration of storage piles, and to regularly monitor the internal temperature of the material.

Compact wood generally represented a more stable form in terms of spontaneous ignition and flash ignition. However, under long-term thermal stress, gradual degradation, charring, and subsequent initiation of combustion may occur. The risk is therefore significant particularly during drying processes, storage near heat sources, or contact with hot technological components. For wood-processing enterprises, this implies that fire prevention measures must be differentiated according to the form of the processed material.

A limitation of the research is that selected fractions of spruce wood were tested under laboratory conditions, without considering the operational conditions of a specific wood-processing facility, such as air flow, the presence of hot surfaces, the method of sample arrangement and storage, or the presence of dust in dispersed form. Another limitation

is the limited number of repeated measurements and the restriction of the research to three forms of a single wood species. The obtained results indicate that, within wood-processing enterprises, spruce wood cannot be regarded as a uniform material; rather, its specific physical form must be considered. Wood sawdust, wood chips, and compact wood exhibit different susceptibilities to thermal decomposition, flash ignition, and spontaneous ignition, which has direct implications for the safety of storage, handling, and technological processing. These differences emphasize the need for a material-specific approach to fire risk assessment in wood-processing practice, as ignition behaviour is strongly influenced by particle size, specific surface area, and heat transfer conditions. The results further enable the formulation of preliminary engineering recommendations for wood-processing facilities and demonstrate that fire prevention measures should be adapted to the physical form of the processed material. Particular attention should be paid to operations generating sawdust, where efficient dust extraction, regular removal of deposited dust, and prevention of equipment overheating are essential due to the material's high specific surface area and increased susceptibility to thermal degradation and ignition; in addition, the accumulation of fine dust in enclosed or poorly ventilated areas may significantly increase the risk of dust layer ignition or the formation of a combustible dust–air mixture, underscoring the importance of continuous housekeeping and preventive maintenance. In the case of wood-chip storage, continuous monitoring of pile temperature, moisture content, and ventilation conditions is recommended to mitigate the risk of self-heating and spontaneous ignition, particularly when large volumes of material are stored, while preventive measures such as optimization of pile geometry, limitation of storage height, and periodic turning or aeration of the material should be implemented to enhance heat dissipation and prevent the formation of localized hot spots. Although compact wood exhibited the highest resistance to ignition among the tested samples, prolonged exposure to elevated temperatures may still result in thermal degradation, charring, and eventual combustion, highlighting the importance of strict temperature control during drying and other heat-related processes, as even relatively stable material forms may become hazardous under insufficient process control or prolonged thermal stress. While the present study does not provide sufficient data for establishing universal engineering threshold values, the experimentally determined ignition characteristics can serve as a valuable reference framework for fire risk assessment and the development of operational safety criteria, and the findings further confirm that the physical form of spruce wood is a critical parameter influencing its fire behaviour and should therefore be explicitly considered in the design of fire prevention and monitoring systems; future research should focus on validating these results under industrial conditions and on defining quantitative engineering limits applicable to wood-processing practice, taking into account additional influencing factors such as airflow, dust concentration, storage configuration, and environmental variability.

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