Determination of the Ignition Temperature of Hay for the Purposes of Fire Risk Assessment on Farms - Slovak Case Study

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Hot surfaces are an integral part of the technological processes of agricultural crop processing. Their surface temperature at critical points can exceed the minimum ignition temperature. This paper aims to experimentally observe the behaviour of hay when exposed to radiant heat. The model presented here is implemented using a hot plate device. The hot plate has a defined temperature-time curve. Based on the above, the hot plate temperature is determined as the minimum ignition temperature of the investigated hay specimen. At the same time, the temperature inside the tested material was monitored. The heterogeneity of the above specimens significantly influenced the nature of the biomass thermal degradation. The ignition temperature of the hay (406 °C) can serve as a tool for fire risk assessment.

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INTRODUCTION

Agriculture has undergone a significant change in terms of the work organisation. Today, agricultural production is carried out through medium and small enterprises (SBA 2021). Although the production and breeding of agricultural animals are decreasing (Statistical Office of the Slovak Republic 2022b), the risk of the fire remains The European Green Deal policy favours the use of agricultural products (EC 2019). Concerning renewable sources, biomass is used as a fuel (Mullerová *et al.* 2010; Martiník *et al.* 2014; Marková *et al.* 2018a), while it is also promoted in the construction industry as an innovative natural insulation material (Daňková and Hejhálek 2009; Cascone *et al.* 2019; Tobias and Writer 2020). The fact that it is a material that does not resist heat must be considered (Preventing fires in baled hay and straw 2012; Štulajter *et al.* 2015; Čekovská *et al.* 2017; Marková *et al.* 2018b; SDSU Extension 2020). The impact of burning and fire suppression on aquatic and terrestrial environments also requires attention (Veľková *et al.* 2019; Hybská *et al.* 2020, 2022).

From an occupational health and safety perspective, agriculture and forestry are highly problematic sectors that require increased attention. As the graph of the enterprise development in agriculture, forestry and fishing (Fig. 1) demonstrates, the number of these enterprises is increasing in the long term, as indicated by the trend line with high reliability

(R^2= 0.95). Over the last decade, more than 3000 enterprises have emerged in that sector. The majority of them are small enterprises (EU-OSHA 2021).

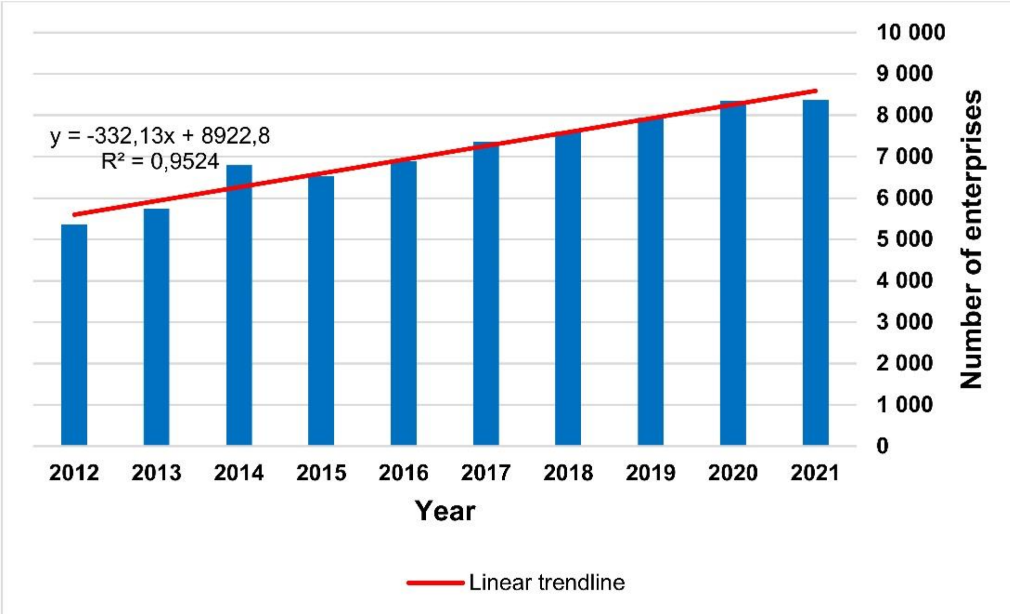

Fig. 1. Development of enterprises in the section of agriculture, forestry and fishing over the last decade (Statistical Office of the Slovak Republic 2022a).

Another reason why increased attention needs to be paid to safety in this sector is a large number of occupational accidents, including serious and fatal ones. Figures 2 and 3 indicate the total number of accidents in each division of the statistical classification of economic activities (SK NACE) for the last decade (2012-2021). Only the first 6 divisions with the highest number of injuries are demonstrated.

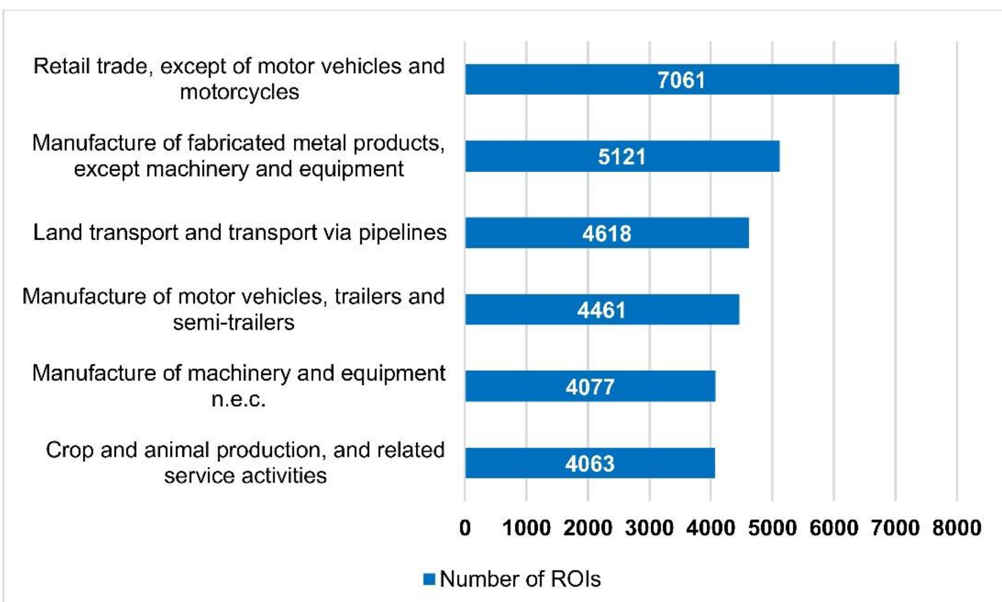

Fig. 2. Number of registered occupational injuries (ROIs) in selected SK NACE divisions with the highest number of injuries over the last 10 years (2012-2021) (Source: Statistic of occupational injuries 2012 – 2021)

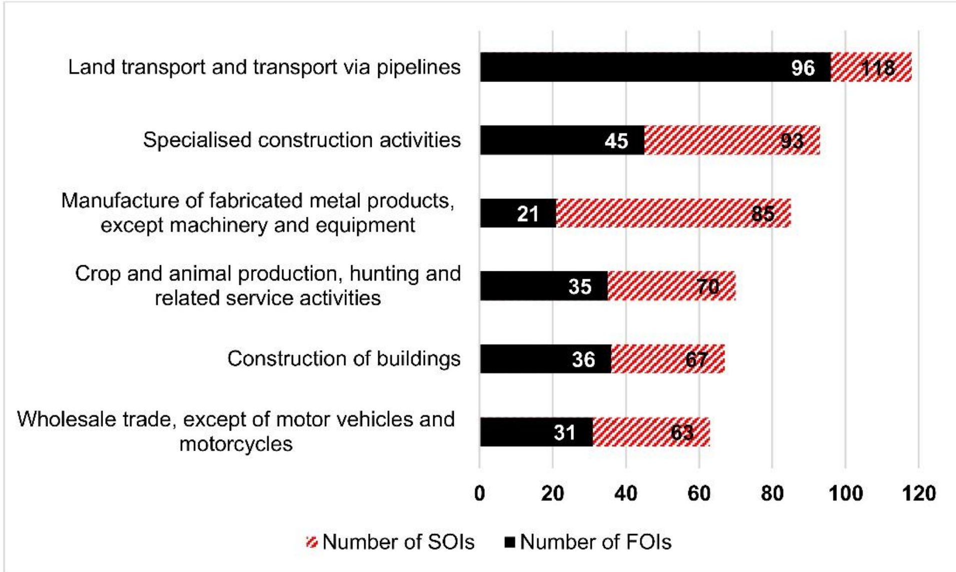

Fig. 3. Number of serious occupational injuries (SOIs) and fatal occupational injuries (FOIs) in selected SK NACE divisions with the highest number of injuries over the last decade (2012-2021) (Source: Statistic of occupational injuries 2012 – 2021)

Figure 2 indicates that the highest number of registered occupational injuries (injuries in which the incapacity for work lasted more than 3 days, hereafter referred to as ROIs) - 7061 over the last decade were in the retail trade division. The six most risky divisions in terms of the number of ROIs, with a total of 4063 such injuries, include Crop and Animal Production, which falls under the Agriculture, Forestry and Fishing Section. This division is also ranked fourth in terms of the total number of serious occupational injuries (SOIs) - 70 (Fig. 3). Of these, as many as 35 were fatal (hereafter referred to as fatal SOIs), which is a relatively high number compared to the other divisions. Although there were almost two-thirds more fatalities in land transport, these were mainly road traffic accidents. The Crop and Animal Production Division can be considered the riskiest within the Agriculture Section. Figure 4 below demonstrates the injury proportions in each sub-classes of this division.

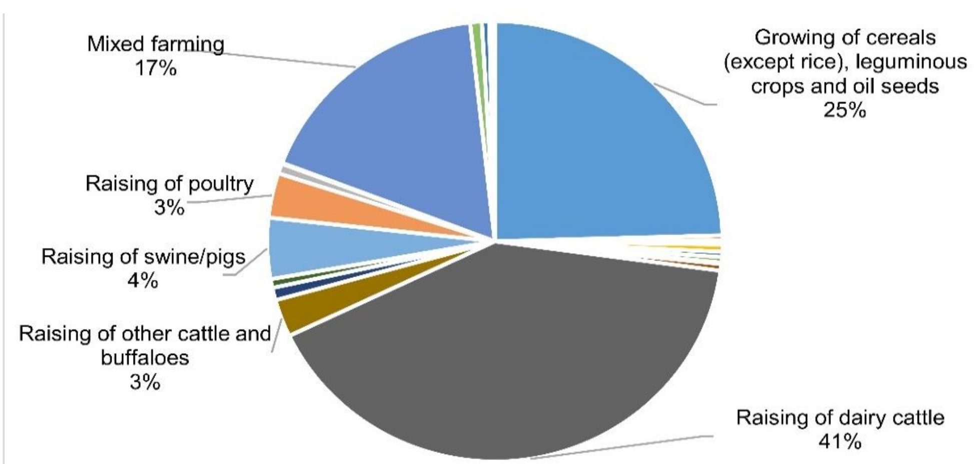

Fig. 4. Percentage of injuries in each subclass of the division 'Crop and Animal Production, Hunting and Related Service Activities' over the last decade (2012-2021) (Source: Statistic of occupational injuries 2012 – 2021)

The highest proportion of occupational injuries, 41%, within the division of Crop and Animal Production, Hunting and Related Service Activities occurs in dairy cow farming. It is followed by cereal farming with an injury rate of 25% and mixed farming with an injury rate of 17%. According to the National Labour Inspectorate, fire hazards are among the most common hazards and dangers in agriculture (Gubrica 2016). Increased fire hazards occur especially during the harvesting of cereals, their post-harvest treatment, and the storage of coarse fodder and straw. These are also used in dairy farming (straw for bedding and hay for fattening), where the highest proportion of occupational accidents occurs.

Figure 5 demonstrates the use of cereal harvesting areas, which pose an increased risk of fire (Holla *et al.* 2017; Vogel and Annen 2018). In 2021, the harvested area of all cereals amounted to 717694 ha.

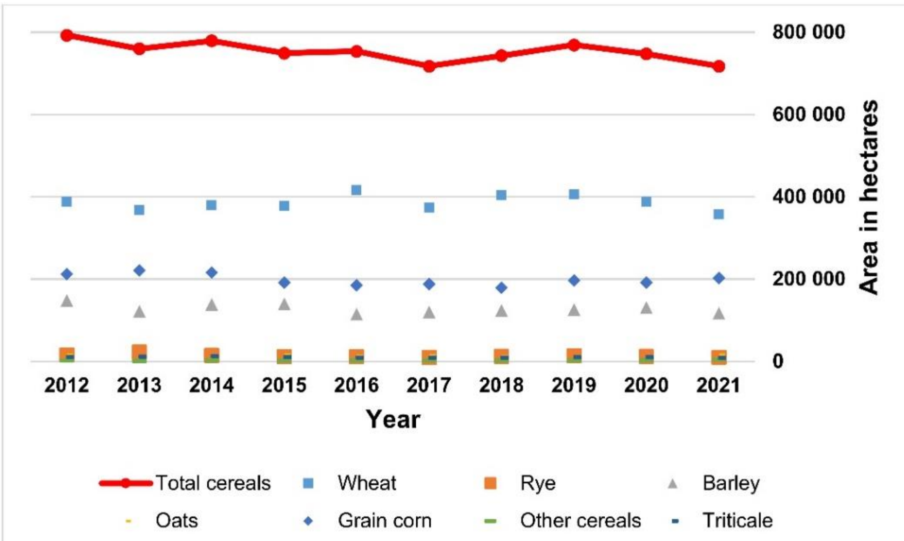

Fig. 5. Harvested area of cereals in particular years (Statistical Office of the Slovak Republic 2022c)

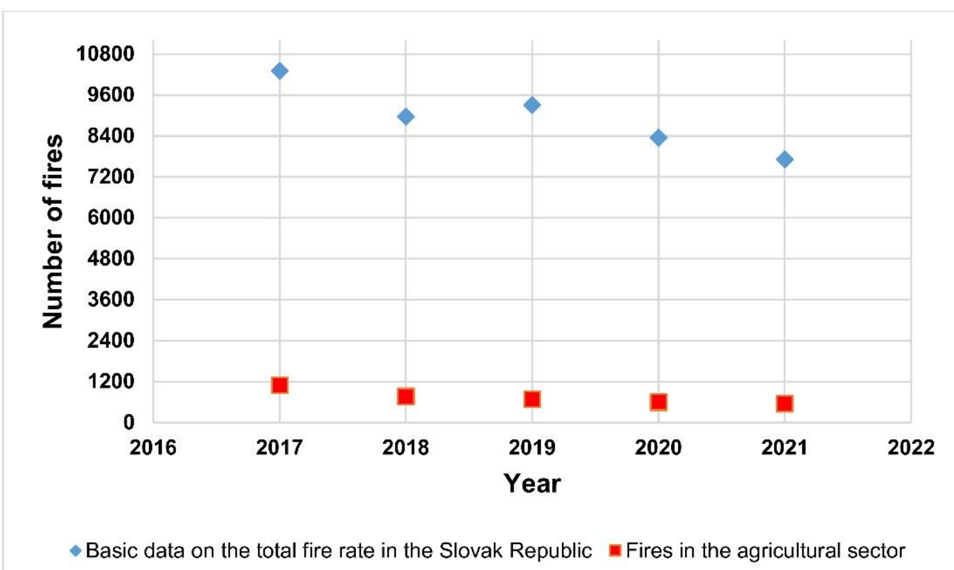

Fig. 6. Fire incidence in the Slovak Republic over the last five years (Source: Fire statistics of the Fire and Rescue Corps 2016 – 2021)

The above fact is confirmed by fire statistics obtained from the Fire Technical and Expertise Institute of the Ministry of the Interior of the Slovak Republic (Fig. 6). Although the number of fires has a decreasing tendency, agricultural fires maintain their respective percentage (11-5%). At the same time, Fig. 7 shows the number of fires based on their causes. During spontaneous combustion and subsequent hay fires, heterogeneous forms of combustion, primarily smouldering, dominate. Smouldering produces large amounts of dense, light smoke.

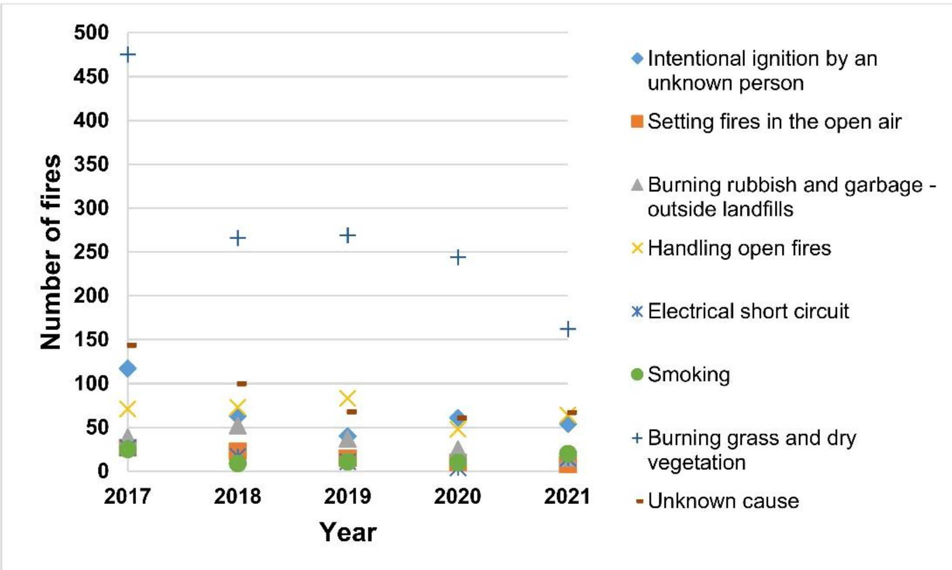

Fig. 7. Monitoring the number of fires by cause of fire in the Slovak Republic over the last five years (Source: Fire statistics of the Fire and Rescue Corps 2016 – 2021)

Hot surfaces are an integral part of biomass processing processes. Their surface temperature can exceed the minimum biomass ignition temperature. Biomass ignition depends on external conditions, but the initiation temperature at which ignition occurs remains the decisive parameter.

This paper aims to experimentally determine the ignition temperature of hay due to the action of radiant heat and cigarettes. Moreover, based on the obtained results, it aims to verify the developed Slovak standards concerning preventive measures regarding the risk of hay fire.

EXPERIMENTAL

Materials

For the experiment, hay specimens obtained from the farm were utilized (Fig. 8c). They were stored in bales and used for running the cow house.

Hay is a green fodder preserved by natural drying or desiccation. Besides fresh green fodder, hay is the most natural feed suitable for all livestock species (Kováč *et al.* 1989). Hay is the dry above-ground parts of plants that are preserved by drying and partial fermentation and, when stored appropriately, represents a long-term supply of high-quality dry roughage (Straková *et al.* 2008).

It is necessary to dry the cut material, *i.e.* to get rid of excess water. This process, which increases the dry matter, is the elementary preservation of hay for long-term storage. The water content of the hay drops to 9-10%. The hay is stored in haylofts with a slatted floor with tunnels into which heating fans blow air, speeding up the drying process.

Hay dried in this way is transported to the cow shed: 1. by pneumatic filling and mechanical emptying (Ďuďák 2022a), 2. by a mixing feed truck (Fig. 8a) (Cow feeding and watering, 2022), 3. by a drive-through feed chute (Herman 2017), or 4. by an electric feed truck by vehicle (Fig. 8b) (Ďuďák, 2022b). Feed must be available to all animals.

a) **b)** **c)**

Fig. 8. Demonstration of feed transport by mixer feed truck (Cow feeding and watering, 2022); (b) Robot feed transport (Cattle feeding, 2022); c) Test specimen.

The hay samples were provided by the agricultural company Agrodružstvo Bánová, Slovak Republic. The samples were dried and stored according to the instructions in Decree of the Ministry of the Interior of the Slovak Republic No. 258/2007 Coll. As stated by the representative of Agrodružstvo Bánová, Slovak Republic, the moisture of the tested samples is 11%.

Methodology

The determination of the minimum ignition temperature of the organic matter layer was conducted by isothermal stressing of the specimen placed on an electrically heated metal hot plate (Fig. 9) and continuous temperature measurement inside the specimen. The minimum combustion initiation temperature is defined as the lowest surface temperature of the hot plate at which at least one of the following phenomena can be observed during the test:

- Glowing, smouldering or flame burning;
- Time-temperature curve for a thermocouple placed in the centre of the specimen layer rises continuously compared to the temperature of the isothermally heated plate;
- Temperature measured in the deposited dust layer is 250 °C higher than the hot plate temperature.

In the conducted experiments, the above conditions were fulfilled.

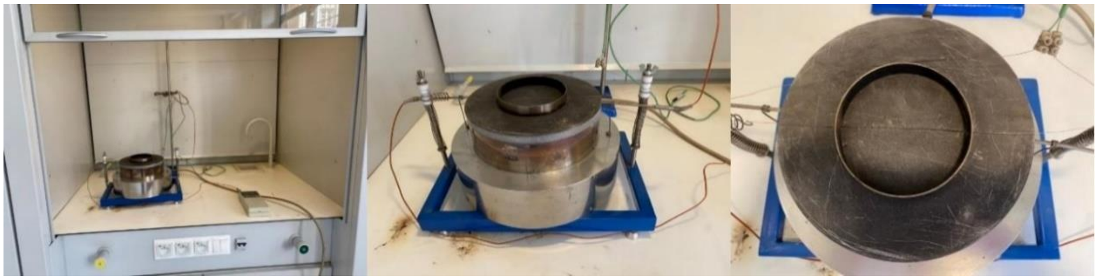

Fig. 9. Hot plate

Hot plate calibration was performed at the beginning of the experiment. The obtained temperature-time curve (Fig. 10) is the basis for the measurement of the ignition temperature according to EN 50281-2-1 (1998).

Subsequently, selected biomass specimens were exposed to the thermal surface. The experiments were performed t at T=21 °C and pressure of 100.56 kPa. They were repeated 3 times.

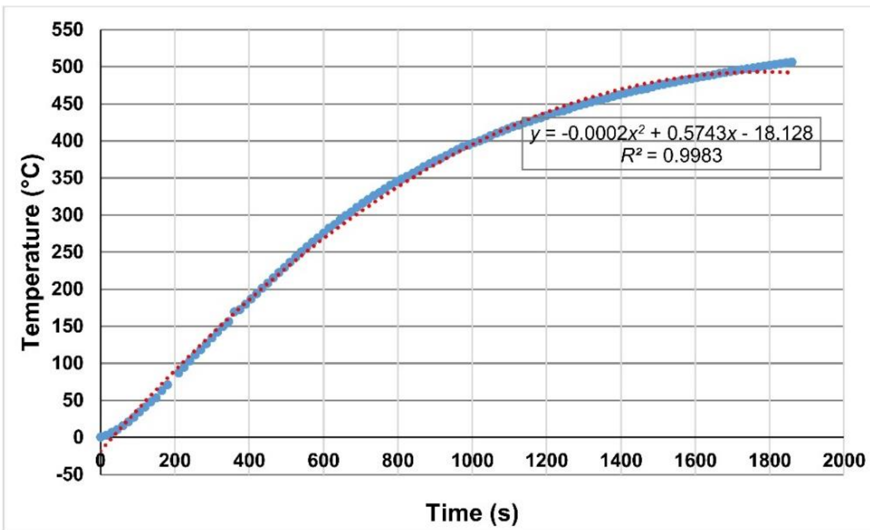

Fig. 10. Dependence of the temperature rise of the hot plate surface on time

The second part of the experiment was based on observing the behaviour of a hay specimen on which a cigarette was placed. The hot plate device was left off as it served as a pad for depositing the specimen.

During the experiment, two temperature values were measured by thermocouples:
1. Surface temperature of the hot-plate;
2. Temperature inside the sample (by thermocouple placed inside the sample).

RESULTS AND DISCUSSION

Table 1 demonstrates the measured values of the minimum ignition temperatures of the hay specimens, the temperatures measured inside them, and a description of the behaviour of the hay layer during its thermal stress and the moment of ignition. The visualization is accompanied by photo documentation (Fig. 11). The specimen weight was increased by 1g. This fact was not reflected in the experiment.

Table 1. Summary of the Results Obtained for the Determination of the Ignition Temperature of Hay

Biomass: Hay	Specimen Weight (g)	Ignition Temperature (°C)	Temperature at the centre of the specimen (°C)	Visual Observations During Measurement
Hay 1	2	400	107.6	After 600 s (10 min), smoking (Fig.11a) and thermal degradation (black surface) spreading from the edges towards the centre of the specimen occurred
			143.6	780 s, incandescence was recorded (Fig. 11c)
			187.8	1050 s (17.5 min) combustion and total charring of the specimen
Hay 2	3	390	98.90	At 435 s (7.25 min) - smoking process starts, thermal degradation proceeds from the edge of the ring to the interior (Fig.11d)
			146.1	At 705 s blackening of the layers touching the plate
			171.4	At 855 s charring of the specimen and incandescence occur
			189.5	At 1020 s, the combustion process is monitored
Hay 3	4	420	111.3	At 480 s (8 min) specimen thermally degrades, smoke formation is observed (Fig.11g)
			160.8	At 810 s charring of the layer on the hot plate surface occurs
			185.4	At 1005 s charring of the specimen edges and gradual degradation of the entire surface and monitoring of the incandescence process take place
			192.6	1080 s the combustion process starts

Fig. 11. Illustration of the combustion process at the critical temperature location. Key: specimen Hay 1 (a);(b);(c); specimen Hay 2 (d); (e); (f); specimen Hay 3 (g); (h); (i).

A thermocouple placed inside the specimen recorded the temperature reached during the period indicated. Hay is a heterogeneous material filled with air. Moreover, it is considered an insulator, which was reflected in the results. The temperature rose slowly and with significant deviations (Fig. 12).

The following processes were monitored during all experiments: odor, smoke, charring of the bottom layer of the sample, charring of the edges of the sample and ignition.

Figure 12 shows the color marked temperature points, the temperature values on the hot-plate. These represent when the processes of thermal degradation and ignition occurred. It is about identifying the surface temperatures when the mentioned changes in the sample can occur. The time-temperature curve marked T1 - in blue color represents the course of temperatures in hay sample No. 1 with a weight of 2g. The blue points on the black curve identify the hot-plate temperature when the thermal change in the sample occurred in the order: smoking, charring, and ignition). The time-temperature curve marked with green T2 represents the temperatures inside the second hay sample (3 g) and the red points present the temperatures on the hot-plate, when degradation changes and processes occurred in the second hay sample. This also applies to the Time-temperature curve marked with red T3.

The time-temperature curve marked T_p in black presents the temperature of the hot-plate surface.

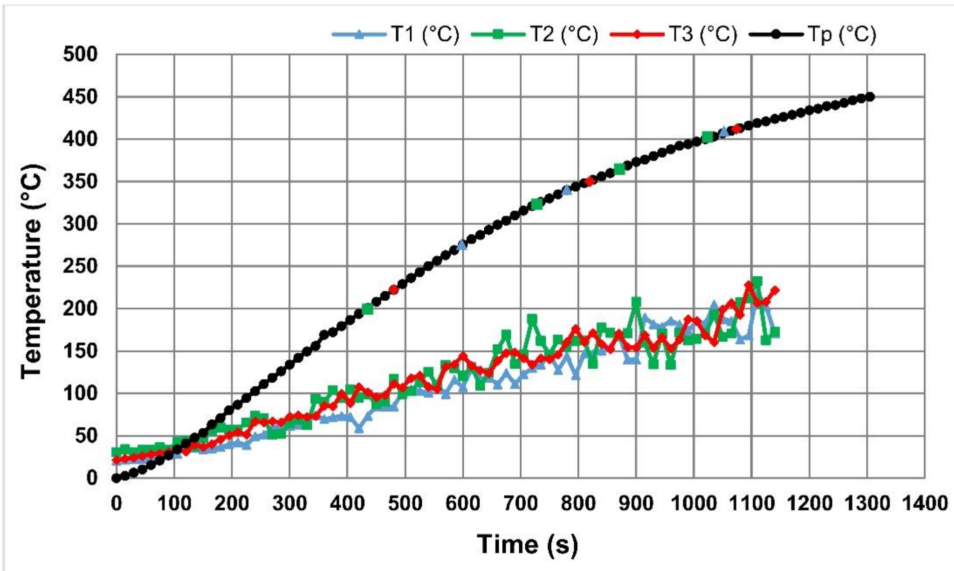

Fig. 12. Time-temperature curves obtained by thermocouples of a hot plate device.
Key: black - values of hot plate surface temperatures, colored points represent temperatures where the specimen was observed. Legends: black curve - hot-plate surface temperature values obtained by calibration of the device, blue points - process of smoking, charring and ignition of sample No. 1, green points - smoking process, charring of the lower layer of the sample, charring of the edges of the sample, ignition point of sample No. 2, red points - process of smoking, charring and ignition point of sample No. 3

Hay specimens with different weights behaved similarly during the experiment. Before the start of the smoking process, an unpleasant odour was observed at an average temperature of 62.1 °C for all tested specimens, increasing with the rising specimen temperature. The subsequent intensity of the smoking process was moderate, and the smoke colour was light blue. As the temperature of both the surface and the specimen rose gradually, the smoke increased to the point of ignition when the first outbreak formed in the test specimen. Subsequently, the smoking intensity decreased until it disappeared completely, and only the glowing embers and stalks of the tested specimens, located 10 mm above the hot surface, remained. The ignition temperature value of 407 °C for hay is higher than reported by The Czechoslovak Union of Fire Protection (1980) - (310 °C).

According to statistical data (BORGA 2022), most straw and hay fires occur within six weeks of baling. There are multiple causes of hay fires, but spontaneous combustion of hay bales remains the priority cause. The main factor in hay self-ignition is moisture. However, if the hay contains more than 20% water, it creates an ideal environment for mesophilic bacteria to multiply and produce additional heat. Thus, the temperature inside the bale can reach up to 60 °C (BORGA 2022) and even climb to 80 °C (Hartschuh *et al.* 2019). In the long term, however, this temperature does not suit the bacteria, so they frequently start to die gradually, and the bale temperature drops. The data presented in Table 2 are based on the Slovak legislation on solid fuel storage. The present experiments demonstrated the start of degradation processes from the temperature of 98.90 °C (Table 1), in agreement with the legislative data.

Table 2. Critical Hay Temperatures

T (°C)	Description of Hay Behavior (BORGA 2022; Hartschuh *et al.* 2019)	Identification of Critical Temperatures (according to Decree 258/2007 Coll.)
50	No need to address	
65	Beginning of temperature danger zone: Check temperature twice daily. Spread the bales out so they can be cooled by airflow.	When the stored wilted fodder in one of the sections of the plant storehouse heats up to a temperature higher than 65 °C, the drying device in this section must be switched off and the overheated wilted fodder must be removed from the storehouse (Article (2) § 8 of Decree 258/2007 Coll.).
70	Danger Temperature Zone: Check the temperature every few hours. Spread the bales out so they can be cooled by airflow.	
80	Emergence of hot spots and fire seats: Contact the fire brigade to report that there is a risk of fire. Try to prevent air from circulating around bales. At this stage, the ignition may occur.	
88	High risk of ignition. With the help of firefighters, it is necessary to remove the glowing hay bales.	When the temperature of stored wilted fodder rises above 90 °C, it must be removed in the presence of the firefighting unit (Article (3) §8 of Decree 258/2007 Coll.).
93 and more	The highest risk of ignition. With the help of firefighters, remove glowing hay bales. Ignition is very likely.	

Other factors that affect the temperature inside the bale are the length of the stems, the bale density, and the ventilation of the surrounding air. For bales with less compacted and shorter stalks, and the well- ventilated storage area, the risk of fire is significantly lower (BORGA 2022).

The experiment conducted with cigarettes was indicative. The cigarette was burning gradually, which can be visually observed in Fig. 13, but the thermocouple inserted in the specimen did not record a temperature rise. It can be assumed that the cigarette glowing will cause the development of a certain amount of heat, leading to turning the specimen surface black at the location of the cigarette (Fig. 13(d)).

Fig. 13. Demonstration of the burning cigarette experiment. Key: (a) before experiment; (b) experiment at 1 min; (c) experiment at 3 min; (d) specimen at 5 min, after experiment.

CONCLUSIONS

Slovakia is a country with developed agriculture, cattle breeding, and crop production. However, the work needed to maintain and develop the sectors mentioned above can be considered hazardous. The number of occupational accidents in the last decade calls for increased attention to the involved risks.

At the same time, the area of cultivation and storage of crops must accept the risk of fire, as shown by the statistics presented. The current Slovak standards develop preventive measures to avoid spontaneous combustion or ignition of crops (Table 2). The correctness of the formulated standards is also proved by experimental results on selected forage - hay.

Based on the experimental results, it is possible to state:

- After 7 min of experiment, the degradation process started. Here, the specimens reached a temperature from 98 to 111 °C, and the hot plate temperature was 250 to 300 °C.
- The experimentally determined ignition temperature for hay was 406 °C.
- During the experiment, smoking and incandescence up to the initiation of homogeneous (flame) combustion were monitored.

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