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Comparative Analysis of the Explosion Parameters of Selected Gluten-Free Flour Dusts

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Abstract

Flour dust explosions are chemical explosions characterized by violent thermal decomposition and oxidation reactions, accompanied by a sudden increase in pressure and temperature. Combustible dusts undergo thermal decomposition, releasing flammable gases; thus, in this context, a dust explosion is similar to an explosion of a flammable gas–air mixture. Flour explosions in the food industry have been the subject of many studies, but there is limited number of publications on the explosion safety of gluten-free flours. Five dusts were selected for comparative characterization under common standardized conditions: green pea flour, soybean flour, millet flour, lentil flour, and maize flour. The following parameters were determined: the minimum ignition temperature, the maximum explosion pressure (p_{max}) and its derivative $(dp/dt)_{max}$, and the lower explosion limit; Thermogravimetric Analysis; and heat of combustion tests. The tested flours show different values of basic flammability and explosiveness parameters, e.g., the green pea flour 5 mm dust layer ignited from the heated surface at temperatures as low as 310 °C. The lowest temperature of maximum mass loss (291 °C) was recorded for green pea flour. The obtained K_{St} values range from 55 to 81 bar·m·s^{-1} (class St 1), the LEL is between 125 and 250 g·m^{-3}, and the 5 mm dust layer MIT values range from 310 to over 400 °C. The results show that there is a need to apply dedicated explosion protection means in plants where the processing, and transportation of the gluten-free flours takes place.

Keywords: explosion protection; gluten-free flours; storage safety; dust explosion; K_{St}; minimum ignition temperature; 20 L sphere; thermogravimetry

1. Introduction

Dust explosions are unavoidable in many industries and have been a frequent area of global research [1–4]. In particular, in the field of testing the basic parameters of flammability and explosiveness, according to commonly known research methods [5–10], there are fewer test results for gluten-free flours, which are becoming more popular. In the food industry, dust can be generated during grinding, mixing, sieving, drying, and sorting and can even come from the grains or seeds from which flours are made.

The literature describes the explosive parameters of some gluten-free flours, namely: rice flour [11,12], chickpea dust [13] and starch [14], where the p_{max}, $(dp/dt)_{max}$, K_{St}, LEL, MIT and MIE values are 6.1 to 11.25 bar [11,13], 63.5 to 313 bar·s^{-1} [12,13], 22 to 85 bar·m·s^{-1} [11,13], 60 to 600 g·m^{-3} [11,13], 400–480 °C [14] and 30–60 mJ [14], respectively. The novelty of this scientific article is therefore primarily an comparative analysis, under standardized experimental conditions, of the

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explosion hazards of gluten-free flours, the production of which has been increasing in recent years. Flour samples were, therefore, selected to fill this research gap.

The thermal characteristics of combustible materials, such as flours, have been widely published in the literature [15]. The research also concerns the effect of the flour grain shape, depending on the method of its production and physicochemical parameters, including the quality of bread obtained from wholegrain wheat flour [16].

The literature also describes the thermal hazards associated with colored maize flour in the food industry, using the Starink, FWO, and Kissinger method and the TG-FTIR apparatus [17]. It is possible to determine the value of thermo-kinetic constant. The constant is used is to categorize the sample [18].

Fire and explosion safety related to processing food products, such as flour, is associated with the risk of igniting a layer of dust deposited on a surface at a sufficiently high temperature [19]. It does not necessarily have to be the surface of the device from which combustible dust is removed, in accordance with common industrial practice. Such procedures are common practice. A much less noticeable threat is associated with the possibility of a dust layer settling on electrical wires, which are more likely to reach high temperatures in emergency situations rather than normal ones [20].

According to the authors, insufficient attention is paid to gluten-free plant flours in the context of explosion safety. The range of gluten-free products is increasing; therefore, understanding the flammability and explosiveness parameters of gluten-free flours, which can be manufactured or processed in the same plants as cereal flours, is necessary to ensure their safe use. Dust producers must bear in mind that the desire to expand production with other types of flour may result in the need to replace equipment and adapt explosion protection measures.

It should be emphasized that to protect against explosions, there is an appropriate implementation order for both organizational and technical safety measures. Firstly, creating an explosive atmosphere must be prevented. Secondly, potential sources of ignition of these mixtures should be controlled. Lastly, the explosion effects should be limited [21,22]. An example of the latter solution is explosion venting technology, which is successfully used in grain elevators [13,23].

The issue of explosive grain products in the industry has existed since milling processes were carried out on a large scale. Basic problems have been identified for decades [24], but obviously, this has not reduced the number of events to zero [25].

The ignition of a cloud of organic dust occurs in the following order [13]: heating of the material, which causes the release of heat, leading to thermal decomposition of the dust; the release of volatiles from the solid as a result of the thermal decomposition; mixing of combustible volatile products with oxygen in the air; and finally ignition initiation, leading to gas phase explosions. However, the combustion reaction of dust clouds or their layers does not always form an explosive atmosphere. Sometimes, the combustion process ends with burnout and does not entail further consequences. Unfortunately, if this process occurs fast enough and there is sufficient heat released, the dust poses an explosive hazard. It is important to prevent a combustion reaction from forming, and in the case of its occurrence, react very quickly to prevent its spread.

This article is intended to be a response to this gap in the global literature and aims to raise awareness of the risks associated with food processing using gluten-free flours. The article presents the results of a comparative study conducted to determine the explosive properties of selected gluten-free flours, tested under common standardized conditions, to reveal the explosion hazards associated with food processing industry.

Industrial safety is directly linked to the achievement of the UN Sustainable Development Goals. This connection is particularly evident regarding SDG 3 (Good Health and

Well-being) and SDG 8 (Decent Work and Economic Growth), as safe working conditions reduce the number of accidents and the incidence of occupational diseases. Safe working conditions also foster an environment of decent, stable employment and support the long-term productivity of an organization [26,27].

The impact on other goals—namely SDG 9 (Industry, Innovation and Infrastructure), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action)—is usually indirect: safer processes limit the number of failures, periods of downtime, and unnecessary emissions of pollutants into the environment, as well as reducing waste generation and raw material losses. Such conclusions can be drawn from numerous studies examining the consequences of industrial accidents [28,29].

Proper process safeguarding is crucial for business continuity—a conclusion that is fairly self-evident. In practice, however, some managers show reluctance to invest in safety, viewing it as an area that is seemingly difficult to visualize or quantify (since it is impossible to compile statistics on events that did not occur). Nevertheless, evidence exists linking such investments to impacts on the production process [30]. Integrating safety considerations with environmental management, quality management, maintenance, and business continuity planning may prove to be the most effective approach [31–33].

2. Materials and Methods

2.1. Materials

Five types of combustible dust from gluten-free flours were selected for this study as follows: green pea flour dust; soybean flour dust; millet flour dust; lentil flour dust; and maize flour dust. The samples were commercial flours sieved in the laboratory. The samples were not dried before the tests.

The tested dust came from the BadaPak (Ożarów Mazowiecki, Poland) plant. Flour dust was sieved through a sieve with a mesh size of 63 µm. Granulometric analysis was performed using a Laser diffraction particle size analyzer Analysette 22 device manufactured by Fritsh. Table 1 describes the chosen characteristics of the tested samples, i.e., bulk density, contents of transient moisture, basic nutrition facts, and analysis outcomes.

Table 1. Characteristics of tested dust samples.

Parameter	Green Pea Flour	Soybean Flour	Millet Flour	Lentil Flour	Maize Flour
Bulk density, g·dm^{-3}	593	356	507	428	540
Moisture content, wt%	8.6	7.2	10.2	10.1	10.02
Protein content in 100 g, g	23	25	8	25	9
Carbohydrates content in 100 g, g	46	63	74	63	70
Fat content in 100 g, g	2	1	3	1	4
Ultimate analysis, wt%	%C 41.24 %H 6.59 %N 3.11 %S 0.25	%C 42.54 %H 6.92 %N 2.92 %S 0.32	%C 42.19 %H 7.13 %N 1.67 %S 0.26	%C 49.22 %H 7.70 %N 6.87 %S 0.40	%C 40.54 %H 6.02 %N 2.82 %S 0.22

The bulk density was determined using a vessel of known volume and a laboratory balance. The transient moisture content was determined using a laboratory moisture analyzer manufactured by Radwag (Radom, Poland). Nutrition facts have been declared by the manufacturer. The analysis of C, H, N, S (ultimate analysis) content was performed using the UNIcube analyzer manufactured by Elementar. The test is performed twice to confirm the consistency of the results and the representativeness of the samples.

Figure 1 presents the results of the particle size analysis of the tested gluten-free flours.

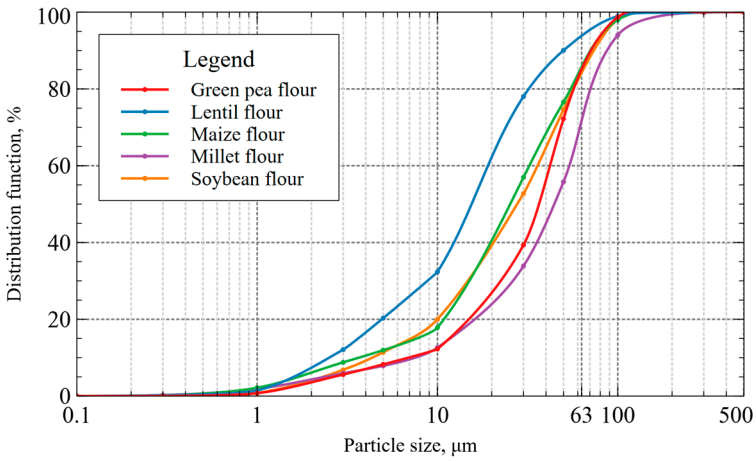


Figure 1. Particle size distribution of the test samples.

The values of the particle size distribution function (d10, d50, d90) are presented in Table 2. The result is the arithmetic mean of three consecutive measurements.

Table 2. Summary of particle size distribution of the test samples.

Parameter	Green Pea Flour	Soybean Flour	Millet Flour	Lentil Flour	Maize Flour
d10, µm	7.0	4.3	7.5	2.6	3.7
d50, µm	35.8	28.0	45.0	16.7	25.5
d90, µm	69.8	72.3	89.7	49.9	72.2

The data presented in Table 2 clearly show that lentil flour exhibits the highest degree of fineness—i.e., 90% of the particles are smaller than 50 µm—whereas for the other samples, the d90 value ranges from 69.8 to 89.7 µm.

2.2. Methods

2.2.1. Explosion Parameters

The explosiveness parameters of the selected flour dusts was determined on the basis of the EN 14034 standards [6–8] and a comparative analysis these parameters was performed. The main element of the test apparatus manufactured by ANKO LAB (formerly ANKO), model 2/2021 was a sphere with a volume of 20 dm^3 connected to a dust container with a volume of 0.6 dm^3. The dust samples, with a mass resulting from the tested dust concentration, were introduced to this container through an electro-pneumatic valve and a dispersion nozzle at an overpressure of 2 MPa. The delay between the time of introducing the sample into the test chamber and the ignition of the chemical igniters was about 60 ms. The igniters consisted of ignition heads installed inside the spherical chamber. Pressure sensors manufactured by PCB Piezotronics were used.

Determining the lower explosion limit (LEL) in conformity with the standard [8] requires a single igniter with a rated energy of 2 kJ. For testing p_{max} and $(dp/dt)_{max}$, a couple of igniters was used, each with a rated energy of 5 kJ. The used chemical igniter was produced by Sobbe GmbH (Dortmund, Germany). The ignition of the dust–air mixture inside the test chamber resulted in a pressure increase greater than or equal to 0.5 bar compared to the initial pressure. In order to determine p_{max} and $(dp/dt)_{max}$ of the tested dust, a series of measurements was carried out, starting with the measurement for a concentration of 250 $g \cdot m^{-3}$. In subsequent measurements, the concentration of the tested dust was increased by 250 $g \cdot m^{-3}$ or decreased by about 50% of the previous concentration. Example

concentration sequences for testing are as follows: ...; 60; 125; 250; 500; 750; 1000; 1250; 1500; ...g·m^{-3}. The test could be terminated if two consecutive measurements on either side of the maximum value of the recorded explosion pressure were lower than this value (minimum of five consecutive measurements for different concentrations of dust).

In accordance with the standard [6], in order to select the maximum dust explosion pressure in a sphere with a volume of 20 dm^3, three series of measurements had to be carried out, and the obtained results were used to calculate the average and calculate the corrected value of p_{max}. A correction was made to take into account the cooling effect associated with the test apparatus. The calculated value $(dp/dt)_{max,20l}$ was the maximum value of the rate of pressure increase recorded during the tests. To calculate $(dp/dt)_{max}$, taking into account the correction factor, the following formula was used [7]:

$$K_{St} = \sqrt[3]{0.02} \cdot \left(\frac{dp}{dt}\right)_{max,20l} = 0.2714 \cdot \left(\frac{dp}{dt}\right)_{max,20l}, \quad (1)$$

On the basis of the K_{St} value, dust explosiveness was classified into three groups as follows: dusts with the highest, medium, and lowest severity of potential explosion (Table 3).

Table 3. Dust explosion classes.

Dust Explosion Class	K_{St}, bar·m·s^{-1}	Meaning (Generalized)
St. 0	0	Does not explode
St. 1	1–200	Weak explosion
St. 2	201–300	Strong explosion
St. 3	>300	Very strong explosion

The standard [8] defines LEL as the lowest concentration of combustible dust in air at which an explosion occurs. However, the test method applies a different operational criterion with an added safety margin. Accordingly, in this study the reported LEL is the highest dust concentration at which no ignition occurred in three consecutive tests. The tests started with a dust concentration of 500 g·m^{-3}, and the concentration in subsequent tests was reduced by approximately 50%, i.e., to the following values: 250, 125, 60 g·m^{-3}, etc. The LEL value was the highest concentration for which three consecutive tests had a negative result.

Although the mass of a dust sample can be measured with high accuracy, the nature of the test method implies that not all combustible dust is necessarily consumed during combustion. The uncertainty of standard methods employing the 20-litre apparatus is estimated in the literature at approximately 0.1 bar, corresponding to a relative value of less than 2% [34]. Research practice indicates that in borderline cases, this value should not exceed 5%, similarly for determining the value of dp/dt. When determining LEL, successive dust concentrations are tested—for example, 60, 125, or 250 g·m^{-3}. The criterion for an explosion is a pressure rise of at least 0.5 bar. It is difficult to speak of traditional measurement uncertainty in this context. The determined LEL is therefore of quasi-qualitative nature.

The number of test series conducted to determine dust explosion parameters complied with the requirements set out in technical standards.

2.2.2. Thermogravimetric Analysis

The tests were carried out using a TA Instruments Q500 thermogravimeter. Gluten-free flour samples weighing about 30 mg were analyzed in oxidizing atmosphere in accordance with the dynamic method described in the standard [9]. The test was carried out in a temperature range from 20 to 800 °C with a sample heating rate of 10 °C/min and a gas

flow of 10 mL/min. Inaccuracy of temperature measurements does not exceed 1 K, with measurement resolution of 0.1 K. Typical inaccuracy of mass measurements is estimated not to exceed 0.01% plus baseline drift not greater than 0.05 mg. In summary, based on the authors' previous experience and the documentation of the device manufacturer, the accuracy of the measurement was estimated as:

- 1 K for temperature measurement at maximum temperature of 800 °C;
- 0.01 mg for measuring the mass of the sample, given the mass sample of ~30 mg;
- 1 °C/min for measuring the rate of the sample mass loss.

Nitrogen 5.0 and oxygen of the highest purity (≥99.999%) were used for the study.

2.2.3. Heat of Combustion

To determine the heat of combustion of the gluten-free flour samples, the bomb calorimetric method was used, in accordance with the standard [10]. A KL-14 calorimeter manufactured by the Polish company Precyzja-BIT (Bydgoszcz, Poland) was used. The mass of the tested sample was approximately 1 g. It was subjected to combustion in an oxygen atmosphere at a pressure of 2 MPa and an initial temperature equal to the ambient temperature (approximately 20 °C). A constant volume was maintained in the bomb calorimeter during complete combustion of the sample. The calorific value of the heat of combustion per unit of sample mass was determined after the water vapor generated during combustion was brought to a liquid state.

The results are the average obtained from three consecutive test trials.

2.2.4. Flammability Parameters

The test methods and test standards used to determine the minimum ignition temperature (MITs) of the dust layer and dust cloud (T_{5mm} and T_{CL}) were in accordance with the standard [5]. The device was manufactured by ANKO LAB (formerly ANKO, Warsaw, Poland), model 2/2010. The aim of determining the MIT from the heated dust surface was to determine the appropriate electrical equipment for use in the presence of these dusts. The method for determining the MIT of a dust layer involved examining the dust layer on a heated surface at a constant temperature. The MIT value was considered to be the lowest furnace temperature for which ignition of the dust layer was recorded.

According to the standard [5], ignition of the dust layer should be considered if at least one of the three following criteria classifying the ignitability of the dust layer is met:

1. The temperature of the dust layer reaches 450 °C;
2. The temperature of the dust layer is 250 K higher than the temperature of the heated surface;
3. Glowing or flames are visible in the dust layer.

For the tested flour dusts, the MITs of a dust layer with a thickness of 5 mm and 12.5 mm were determined.

The MIT of a dust cloud was determined using a tube furnace heated to a specific temperature. The test began with a pressure of 30 kPa and a sample mass of 0.3 g. Optimal ignition conditions for the dust sample in the Godbert-Greenwald furnace are determined by varying the dispersion pressure between 10 and 50 kPa and the sample mass between 0.05 and 5 g.

The sample was placed in a container connected at one end to a hose introducing compressed air from the tank and connected at the other end to a ceramic tube through which the dust was blown into the furnace. After opening the solenoid valve, the sample in the form of a dust cloud was introduced to a ceramic heated tube inside the furnace. The

lower end of this tube was exposed, which allowed verification of whether ignition had occurred inside the furnace or whether the dust particles were visibly glowing.

In accordance with [5], the appearance of a flame extending beyond the lower end of the furnace tube was taken as evidence of ignition. The appearance of sparks at the outlet was not considered as ignition. The MIT was the lowest furnace temperature at which ignition was recorded reduced by 20 K or, for an ignition temperature below 300 °C, by 10 K.

In the case of dust flammability testing, the temperature control and measurement devices have declared accuracy of ±3 K, and the uncertainty of the determined parameters should not exceed 5 K (e.g., [35]), regardless of the safety margins applied.

3. Results

3.1. Explosion Parameters

Table 4 presents the results of testing the explosiveness parameters of the tested dusts. The p_{max} and $(dp/dt)_{max}$ values are given together with the value of dust concentration at which the given maximum value was recorded.

Table 4. List of results for determined explosion parameters.

	Green pea Flour	Soybean Flour	Millet Flour	Lentil Flour	Maize Flour
$p_{max,[series1]}$, bar	6.8	5.6	5.6	5.7	7.1
$p_{max,[series2]}$, bar	7.1	6.1	5.7	6.0	7.1
$p_{max,[series3]}$, bar	6.8	6.0	5.8	5.7	6.9
standard deviation, bar	0.1	0.2	0.1	0.1	0.1
p_{max}, bar, at given concentration, g·m^{-3}	6.9 1500	5.9 1000	5.7 1000	5.8 500	7.03 750
$(dp/dt)_{ex,[series1]}$, bar·s^{-1},	315	231	210	259	187
$(dp/dt)_{ex,[series2]}$, bar·s^{-1},	280	272	253	303	216
$(dp/dt)_{ex,[series3]}$, bar·s^{-1},	295	241	213	295	207
standard deviation, bar·s^{-1},	14	17	20	19	12
$(dp/dt)_{max}$, bar·s^{-1}, atgiven concentration, g·m^{-3}	297 1500	248 750	225 1000	286 500	203 1000
LEL, g·m^{-3}	125	250	125	125	125
Value of K_{St}, bar·m·s^{-1}	81	67	61	78	55
Dust explosion class St	1	1	1	1	1

The increases in the maximum rate of explosion pressure for individual samples are comparable. The differences in the values of the maximum explosion pressure are equal to 1.37 bar, but it is worth noting that lentil flour achieves these parameters at the lowest concentrations, which means that 500 g of dust per unit volume already poses a serious explosion hazard. The obtained p_{max} and $(dp/dt)_{max}$ values for green pea flour are comparable, but they were recorded at concentrations that were three times higher. At the same time, the LEL values for the tested gluten-free flours are comparable, but it should be noted that in this case, according to the standard, an energy stimulus of 2 kJ was used.

3.2. TG Analysis

Figure 2a,b show the cumulative results of the obtained TG curves for the tested samples, as well as the curves of the sample mass loss rate over time.

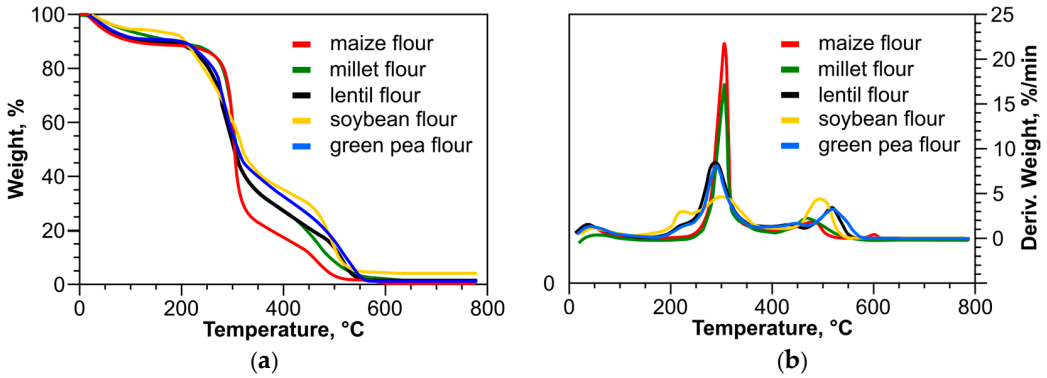


Figure 2. TGA analysis results: (**a**) TG curves; (**b**) DTG curves.

Table 5 summarizes the results of the TG analysis. The temperature at the beginning of the thermal decomposition of the sample is considered to be the point of intersection of the tangents to (a) the TG curve at the point where the derivative of the sample mass loss over time reaches its maximum and (b) the plateau after transient moisture evaporation. The TG results, which define the individual stages of thermal decomposition, are related to the course of the explosion and its dynamics.

Table 5. Results of TGA on samples.

	Green Pea Flour	Soybean Flour	Millet Flour	Lentil Flour	Maize Flour
Temperature at the beginning of thermal decomposition (°C)	258	199	284	255	288
Temperature of 50% sample mass loss (°C)	311	321	308	301	305
Temperature of maximum mass loss (°C)	291	310	304	293	306
Maximal mass loss rate, %/min	8.04	4.55	17.09	8.58	21.86
Temperature at the end of thermal decomposition, °C	571	549	651	568	602
Mass of the residue, %	0.89	4.16	0.44	0.01	0.64

There are some significant differences in the thermal decomposition of the tested samples. Soybean flour dust undergoes thermal decomposition at the lowest temperature, i.e., at 199 °C, while millet flour dust and maize flour dust require temperatures above 280 °C. Within a range of approximately 20 K, i.e., between 291 and 310 °C, all samples reach the maximum rate of sample mass loss over time. A significant difference is noticeable after comparing the values of these rates of mass loss over time. Higher values were obtained for millet flour dust and maize flour dust—values that were several times higher than for soybean flour dust. This is related to the intensity of the release of volatile combustible particles when the samples are heated. At the same time, for the soybean flour dust mentioned above, the value of the sample residue is the highest.

Based on the TGA results and the sample compositions declared by the manufacturer, one may tentatively conclude that an increasing fat content (and thus a lower proportion of protein and carbohydrates) leads to a reduction in the onset temperature of thermal

decomposition. The increase in fat content may also be inversely correlated with the elemental carbon content.

3.3. Heat of Combustion

The values of the heat of combustion determined in the calorimetric bomb are presented in Table 6. The heat of combustion of the samples is one of the factors influencing the amount of energy that can be released during an explosion, thereby affecting its course.

Table 6. Heat of combustion of gluten-free flour samples.

	Green Pea Flour	Soybean Flour	Millet Flour	Lentil Flour	Maize Flour
Heat of combustion 1, kJ·g^{-1}	22.745	17.112	17.980	17.899	15.024
Heat of combustion 2, kJ·g^{-1}	22.386	17.263	17.455	18.160	15.305
Heat of combustion 3, kJ·g^{-1}	21.985	17.357	17.212	18.352	15.340
Average heat of combustion, kJ·g^{-1}	22.372	17.244	17.549	18.137	15.223
Standard deviation, kJ·g^{-1}	0.310	0.101	0.320	0.186	0.141

The obtained heat of combustion values are typical for this type of combustible material. A higher value was obtained for green pea flour dust. At a confidence level of 95%—i.e., within the $\pm 2\sigma$ range, the inaccuracy does not exceed 3.7%.

3.4. Flammability Parameters

Table 7 presents the flammability parameter values of the tested samples. In every case, visible glowing was observed at the lowest temperature at which the ignition criterion was met.

Table 7. Results of determining the flammability parameters of gluten-free flour dusts.

	Green Pea Flour	Soybean Flour	Millet Flour	Lentil Flour	Maize Flour
			Thickness of the dust layer: 5 mm		
MIT of dust layer, °C	310	360	>400	330	>400
			Thickness of the dust layer: 12.5 mm		
MIT of dust layer, °C	300	300	>400	300	>400
MIT of dust cloud, °C	450	490	450	490	380
Maximum surface temperature for layer thickness of 5 mm, °C	235	285	300	255	253

Based on the flammability parameters listed above, it can be concluded that the green pea flour dust sample again stands out from the others. The lowest values of the flammability parameters were recorded for this sample, except for the dust cloud MIT. However, considering the method used to determine the maximum surface temperature at locations where green pea flour dust deposits may occur, this value was also the lowest for this sample. This means that, in this context, green pea flour dust sample also requires special attention in terms of fire protection.

In terms of soybean flour dust, increasing the thickness of the dust layer from 5 mm to 12.5 mm increases its susceptibility to ignition from the heated surface and extends the time needed to observe the ignition of the layer. As the thickness of the layer increases, the ignition temperature of the heated surface decreases, which for this dust decreased by

60 °C. The lower ignition temperature of the deposited layer of dust on the heated surfaces of devices increases the risk of fire hazards. Comparing the bulk density values of the dust samples, it can be seen that, with the lowest value for soybean flour, lower values of the MIT of the layer with a thickness of 12.5 mm were observed. The influence of moisture on sample behavior during the tests is insignificant in terms of the ignitability of the dust layer and applies only to the initial few minutes of the measurements during which water gradually evaporated from the samples. The lack of influence of transient moisture on the MIT test result stems from the fact that moisture evaporation occurs during the first few minutes of the test, when the temperature of the dust layer reaches approximately 100–120 °C. Since the obtained MIT values are no lower than 310 °C, transient moisture has no effect in this regard. The dust samples are characterized by auto-ignition temperatures in the range of 450–490 °C, although a markedly lower value was obtained for maize flour (380 °C). When analyzing the tested dusts, the lowest value of the maximum permissible surface temperature of the heated device was 235 °C, recorded for green pea flour dust.

4. Discussion

As demonstrated, the literature does not adequately address the risks associated with the potential explosion of gluten-free flours. This article does not comprehensively address this issue, but it helps fill the identified research gap.

Determining dust explosibility parameters presents challenges regarding the deterministic assessment of measurement uncertainty. While dust sample mass can be measured with high precision (on the order of micrograms), pressure sampling rates are sufficient (typically 100 kHz), and electronic timing is highly reliable, the very nature of the measurement—involving a pneumatic dust injection system and a test procedure based on successive dust concentrations (e.g., 60, 125, 250, 500 g·m^{-3}, etc.)—renders the results quasi-quantitative. This does not adversely affect test repeatability, and the values obtained provide a sufficient basis in industrial practice for the design of explosion protection measures. The criterion for an explosion is a pressure rise of at least 0.5 bar. It is difficult to speak of traditional measurement uncertainty in this context; in an extreme case, this might be defined as 50% of the concentration corresponding to the LEL. If the explosion criterion is not met at a concentration of 60 g·m^{-3} but is met at 65 g·m^{-3}, the determined LEL value is underestimated. From an industrial practice perspective, underestimating the LEL is acceptable, whereas overestimating it is not.

It is important to note that the raw material from which gluten-free flours are made may vary in its elemental composition depending on the region of the world where it is produced. This is due to differences in soil composition, differences between individual plant varieties, and, finally, environmental differences during plant growth. Therefore, these differences may affect the initiation and course of dust explosion of the finished product.

It should be emphasized that the samples originated from a single production batch. To the best of the authors' knowledge, the production process is repeatable, and product quality is monitored. Nevertheless, certain variations in the parameters of materials produced in subsequent years cannot be ruled out, due to potential differences in the origin and properties of the raw materials.

The results obtained for the explosion parameters of gluten-free flour dusts differ from those observed for other industrial dusts. The values for p_{max} and $(dp/dt)_{max}$ are rather typical, similar to the values obtained for sugar, corn starch, or wheat flour [36,37]. Conversely, the Minimum Ignition Temperature (MIT) values are lower than those found for many common industrial dusts, e.g., corn starch, wheat flour [38], soybean dust or grain (maize, wheat, barley) dust [35] (Table 8). In industrial practice, this necessitates a cautious approach to explosion risk assessment—both regarding the mitigation of explosion

consequences and the suitability of equipment, particularly where surface temperature is considered a potential ignition source of the hazardous atmosphere.

Table 8. Summary of the flammability and explosivity parameter values for selected dust materials [39].

Sample Name	Particle Size Median, µm	p_{max}, bar	K_{St}, bar·m·s^{-1}	Glowing Temperature, °C	Ignition Temperature (BAM), °C
Lactose/corn starch	12	6.1	53	470	380
Maize starch	<10	10.3	200	450	510
Maize starch	<10	9.9	194		
Maize starch	170	8.5	143	400	430
Pea flour	<29	7.6	116	290	450
Potato starch	28	8.2	116	450	500
Soya flour	59	7.8	81	420	430
Wheat flour, type 550	27	7.8	103	460	400
Wheat flour, type 550	56	7.4	42	450	470

Glowing temperature—Lowest temperature of a hot surface on which ignition occurs in a 5 mm thick layer of dust under specified test conditions. Ignition temperature—Lowest temperature of a hot surface at which the most flammable mixture of dust and air ignites under specified test conditions.

The transient moisture content in the samples ranged from 7.2 to 10.2 wt%, which may influence the ignitability of the dust–air mixture and the recorded maximum explosion pressures.

The use of two chemical igniters, each with an energy of 5 kJ, in the 20-L spherical vessel constitutes an ignition source powerful enough to trigger an explosion in less explosive mixtures. In such cases, the use of lower-energy igniters is preferable. Nevertheless, the tested samples achieved p_{max} values exceeding 5.5 bar; therefore, this issue does not affect the final test results. Lower-energy igniters (totaling 2 kJ) were used to determine the LEL.

The EN 14034-3 standard [8] requires the use of specific concentrations to determine the LEL value—for example, 60, 125, and 250 g·m^{-3}. The data presented in the article align with this approach; however, reducing the concentration increments for the tested dust in future studies could be considered to obtain a more comprehensive picture of the hazard.

It should be emphasized that flammability and explosibility parameters are influenced by a number of factors, including transient moisture content, particle size distribution, elemental composition, and the course of thermal decomposition. Generally speaking, the finer the dust particle size, the more favorable the ratio of particle mass to external surface area becomes regarding the dynamics of thermal decomposition and the release of volatiles—and, consequently, the energy generated during an explosion. This influences parameters describing explosion dynamics, such as $(dp/dt)_{max}$ and maximum explosion pressure, where the availability of combustible material in the form of flammable gases plays a key role. The course of thermal decomposition, in turn, is primarily influenced by elemental composition, as well as the proportions of specific nutrient groups: proteins, carbohydrates, and fats.

The explosibility of food dusts—such as flour, sugar or starch—is not merely an occupational safety issue but also a significant aspect of sustainable development, as outlined in the UN Sustainable Development Goals (SDGs). SDG 9 calls for modern, resilient industrial infrastructure, including safe industrial facilities, effective dust extraction, properly designed explosion suppression and venting systems, and dedicated organizational measures. Such solutions enhance plant reliability, foster innovation (including safety-related investments), and mitigate the risk of accidents.

From the perspective of SDG 12, preventing dust emissions and accumulation promotes responsible production and consumption. Good work organization, cleanliness, employee

training to raise awareness, and the monitoring of raw material losses help reduce waste and minimize negative impacts on final product quality. Consequently, dust explosion prevention becomes an integral part of efficient resource management and a factor influencing food production quality.

The link to SDG 13 is primarily indirect yet significant. Explosions and fires result in material losses, production downtime, repair needs, increased energy consumption, and emissions associated with facility reconstruction and the resumption of production. Preventing such incidents can therefore reduce a plant's environmental footprint and support climate action. Responsible management of food dust explosion risks thus bridges the gap between a safe, innovative industry and the efficient use of resources and mitigation of environmental impacts.

In summary, the observed differences in the explosibility and ignitability parameters of gluten-containing (described above) and gluten-free flours must serve as the basis for reviewing the explosion protection measures implemented at the industrial facility. Any technological change in this regard—particularly a change in the material being processed—must entail a verification of whether the existing explosion protection system is adequate. Such action supports efforts to achieve the Sustainable Development Goals established by the UN.

5. Conclusions

This study investigated five different types of gluten-free flour (green pea flour, soybean flour, millet flour, lentil flour, and maize flour) using methodologies described in technical standards. The research goal was to conduct a comparative study and to determine flammability and explosion parameters that impact process safety. The conclusions are summarized as follows:

- The elemental analysis results of the samples show that lentil flour dust is characterized by the highest content of C, H, N, and S. The high content of carbon, hydrogen, nitrogen, and sulfur may contribute to the high calorific value obtained for this sample, equal to 18.137 kJ·g^{-1}.
- This may be associated with the obtained results for the explosiveness parameters, which indicate that for the lentil flour dust sample, the maximum values of p_{max} and $(dp/dt)_{max}$ are reached for a concentration of 500 g·m^{-3}.
- The highest calorific value was obtained for the green pea flour dust sample (22.372 kJ·g^{-1}), which recorded the largest values of $(dp/dt)_{max}$ and K_{St} (81 bar·m·s^{-1}). For this reason, it is very important to comply with safety rules and use explosion protection in food industry plants dealing with the production, processing, transportation, or storage of the tested flours. The p_{max} and K_{St} values directly influence the calculation of the explosion venting area [13], which underscores the practical significance of this article.
- For all tested samples, the DTG curves prove the presence of at least two phases of thermal decomposition at temperatures below 300 °C and in the range of 450–550 °C. The peaks of the DTG curve recorded in these temperature ranges reach values several times higher than those of the other samples for maize flour and millet flour.
- The TG analysis of the tested samples showed some differences over the course of the thermal decomposition. The maize flour and millet flour samples were characterized by a high value of the mass loss rate in the first phase of thermal decomposition (21.86 and 17.09%/min, respectively, compared to values in the range of 4.55 to 8.58%/min for the other samples) and a low value in the second phase.
- The soybean flour sample showed clear differences in residue from the other samples in terms of TGA. A result of ash content equal to 4.16 wt% was obtained, which proves the high content of mineral components in soybean flour.

- In the context of protecting industrial installations from explosions, the lowest permissible surface temperature was determined for the green pea flour dust sample (235 °C). This means that processing this type of material requires special attention to safety conditions. This sample also has the lowest MIT of dust layer, being 310 °C.
- Employers should provide people working in places where an explosive atmosphere may form with appropriate training on protection against explosions. This should be part of the applicable training in the field of occupational health and safety.
- The novelty of the study lies mainly in the fact that the results fill an identified research gap. There is a limited number of research findings in the literature regarding the explosion safety of gluten-free flours, some of which originate from a different study conducted by the authors of this article. The results of the comparative analysis of the selected gluten-free flours also allow for direct application in industrial practice.
- Consideration should be given to continuing research into the explosibility of gluten-free flour dusts, particularly regarding the determination of minimum ignition energy, which is crucial in the context of electrostatic discharge as an ignition source.

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Abbreviations

The following abbreviations are used in this manuscript:

$(dp/dt)_{max}$	Maximum Rate of Explosion Pressure Rise
DTG	Differential Thermogravimetry
LEL	Lower Explosion Limit
MIE	Minimum Explosion Energy
MIT	Minimum Ignition Temperature
p_{max}	Maximum Explosion Pressure
TGA	Thermogravimetric Analysis
TG-FTIR	Thermogravimetry combined with Fourier Transform Infrared apparatus

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