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Determination of the Self-Ignition Behavior of the Accumulation of Sludge Dust and Sludge Pellets from the Sewage Sludge Thermal Drying Station

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Abstract: Sewage sludge may pose a fire risk. The safe storage of biomass waste is a challenge due to self-heating processes. This study aims to assess the propensity to spontaneously combust of sewage sludge in order to determine safe storage and transport conditions. The evaluation of spontaneous ignition hazard was assessed according to EN 15188, by the determination of the self-ignition temperature. Certain parameters assumed to affect the inclination of sewage sludge to self-ignite, including the moisture content, bulk density, elemental composition, and particle size, were discussed. The results showed the risk of self-ignition during the storage and transport of sludge dust and pellets. The usage of the smallest basket volume resulted in the highest self-ignition temperatures, which were 186 °C and 160 °C for sludge pellets and dust, respectively. The comparison of the two forms of thermally dry sludge showed, that despite sludge pellets being easier to store and handle issues, the more favorable conditions for the management in terms of fire risk is sludge dust. Its temperatures for safe storage are slightly higher. The results highlighted that future research should focus on the hazards of silo fires and explosions in terms of silo fire prevention and management.

Keywords: sewage sludge; self-heating; spontaneous combustion; sludge dust; sludge pellets

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1. Introduction

The reasonable price and rich resources of biomass attracts researchers' interest. Biomass, being a rich resource of bio-based compounds, is used in many applications. It may be used as a substratum for the production of chemicals [1] and polymers, including bio-based polyesters and epoxy resins, fuels for transportation, and carbon materials [2].

Sewage sludge is a by-product of wastewater treatment plants. The highly valuable organic and inorganic content enables its usage as a biomass feedstock for energy and resource recovery [3]. Depending on the season, technology applied in treatment plants, and specification of the source area, the composition of sewage sludge may vary. After drying, it may contain 50–70% of organic matter, 30–50% of mineral components, including carbon (from 1% to 4%), 3.4–4.0% of nitrogen, and 0.5–2.5% of phosphorus, and some other nutrients [4].

The water content of raw sludge may be up to 99%; thus, dewatering and drying are essential in order to prepare it for further usage and utilization [5]. However, the storage and transport of dry sludge may pose a risk of self-ignition. The reduction in water content to 10% or less adversely affects fire safety [6].

The increase in interest in biomass utilization has attracted attention to the economic and environmental concerns that arise with biomass storage. The disposal of sewage sludge may pose problems due to the emission of odor emission, possible risk of pathogenic organisms [7], and hazardous and toxic substances content, including dioxins or heavy metals [8]. The levels of environmental contamination vary geographically. However, the release of wastewater residues into rivers is one of the most important routes of the contamination of aquatic resources by As, Cd, Cr, Cu, Hg, Mn, Ni, Pb, and Zn [9]. Heavy metal removal in terms of electrokinetic processes, supercritical fluid extraction, ion-exchange treatment [10], adsorption [11], or other treatments needs to be provided for the safe further processing of sewage sludge.

Several sewage sludge management strategies include its application in agriculture, wet oxidation, pyrolysis, incineration, and landfilling [7]. Thickening is essential in some processes, including agriculture applications, wet oxidation, or pyrolysis [12]. Although sewage sludge exhibits comparatively low calorific value, the co-pelletizing and, therefore, co-combustion with other fuels enhances its performance [13]. The pelleting process is widely used in biomass densification by compression under high pressure. The life-cycle assessment of the pelleting process reveals that its decentralization and the usage of renewable energy resources reduce the environmental impact in all studied impact categories [14].

The self-heating processes and dust explosions of biomass are of particular concern due to the necessity of developing strategies for the safe storage of waste biomass [15]. In the presence of oxygen and/or an ignition source, a higher potential for fire or explosion incidents occurs [16]. Biomass, while stockpiled and stored, maintains contact with air during, in which slow or intensive oxidation may take place, resulting in fires and explosions [17].

Previous studies on fire and explosion characteristics revealed that thermally dried sewage sludge dust poses an explosion hazard, as is classified in the St 1 dust explosion class, according to EN 14034-1 Determination of explosion characteristics of dust clouds Part 1: Determination of the maximum explosion pressure p_{max} of dust clouds [18] and EN 14034-2 Part 2: Determination of the maximum rate of explosion pressure rise $(dp/dt)_{max}$ of dust clouds [19]. The results showed that the maximum ignition temperature for the 5 mm thick layer of sludge dust and the minimum ignition temperature of the cloud, according to ISO/IEC 80079-20-2 Explosive atmospheres Part 20-2: Material characteristics: Combustible dusts test methods [20] were 270 °C and 490 °C, respectively. The minimum explosible concentration according to EN 14034-3 Part 3: Determination of the lower explosion limit LEL of dust clouds [21] was found to be 60 g/m^3. A limiting oxygen concentration of 20% and a minimum ignition energy of more than 1000 mJ were obtained according to EN 14034-4 Part 4: Determination of the limiting oxygen concentration LOC of dust clouds [22] and ISO/IEC 80079-20-2 Explosive atmospheres Part 20-2: Material characteristics: Combustible dusts test methods [20], respectively. The achieved results suggest that studied sludge dust may pose a risk when stored in insufficient conditions.

Dust explosions pose a significant threat to industrial processes. There are various methods of preventing explosions of dust–air mixtures, including methods involving partial inerting with inert gases, such as nitrogen or carbon dioxide, which can be used to mitigate the effects of an explosion inside the equipment [23,24].

According to reports [25,26], 137 combustible dust incidents occurred worldwide in 2021, including 57 fires and 80 explosions. The latest sludge dust fires and explosions were reported in wastewater treatment plants in, i.a., San Francisco (USA, 2021), Bristol (UK, 2020), Hamilton (Canada, 2020), and Koziegłowy (Poland, 2019).

Spontaneous ignition is a complex phenomenon, which occurs as a result of exothermic reactions of material taking place without external heat or other sources of ignition [27]. It is a possible cause of fires and explosions. The self-heating of powders, including coal, metals, biomass, and waste [28], may occur during processing, transportation, or storage [29].

A process safety culture is essential for incidents and accident prevention. In addition to conducting interviews, drawing up questionnaires, controlling behavior, and preparing documents, extending the knowledge of the occurring process significantly affects the level of safety culture [30]. Risk assessments in industrial plants should be based on the characteristics of produced and stored materials in order to achieve a complete scenario of hazard [28]. The risk of spontaneous ignition may be evaluated under adiabatic, isothermal, or isoperibolic conditions. The latter is used in the European standard EN 15188, describing the determination of the self-ignition temperature of dust accumulation or granular materials dependent on their volume. The extrapolation of results is performed afterward, in order to assess the safe storage conditions [31].

A proper understanding of the self-heating behavior of the thermally dried sewage sludge may prevent fires and explosions that occur in wastewater treatment plants. An awareness of all potential fire hazards will enable us to effectively perform risk assessments and fire safety plans. Therefore, this study aims to assess the propensity to spontaneously combust of thermally dried sludge dust and pellets from a municipal wastewater treatment plant in order to determine the safe storage and transport conditions. Moreover, the role of the moisture content, bulk density, elemental composition, and particle size distribution in the self-ignition behavior of thermally dried sludge was investigated.

2. Materials and Methods

2.1. Materials

The study was carried out on selected sludge dust and sludge pellets. Materials were obtained from the thermal sludge drying station of the municipal sewage treatment plant in Spain, Europe. Sludge treatment included mechanical and anaerobic biological processes.

2.2. Methods

2.2.1. Moisture Content Analysis

The moisture content was measured according to the standard drying procedure by the use of a moisture analyzer (Radwag, Radom, Poland) with a readability of 0.001 g. The measurement was conducted by the simultaneous weighing and drying of a sample (2 ± 0.01 g) at a temperature of 120 °C.

The moisture content analysis was determined by the loss on drying. The moisture content was calculated according to the equation:

$$M = \frac{m_0 - m}{m_0} \cdot 100\%, \quad (1)$$

where M is the moisture content [wt. %], m_0 is the sample mass before drying [g], and m is the sample mass after drying [g]. Because a single measurement is not representative, the measurements were conducted in three repetitions. The arithmetic mean was chosen as the most reliable estimator of a population mean that minimizes the possible impact of fluctuations/uncertainties/random errors [32].

2.2.2. Bulk Density Analysis

The bulk density was determined by measuring a volume of a known mass of the sample introduced into the graduated cylinder (100 cm^3). The bulk density was calculated according to the following equation:

$$\rho = \frac{m - m_0}{V}, \quad (2)$$

where ρ is the bulk density [g/cm^3], m is the mass of the sample [g], m_0 is the mass of the graduated cylinder [g], and V is the sample volume [cm^3]. Measurements were conducted in two and four repetitions for the sludge dust and sludge pellets, respectively, obtaining the average bulk density. The measurements were repeated for the same reason as the moisture content analysis.

2.2.3. Elemental Analysis

The CHNS determination by a thermal conductivity detector (TCD) was performed with the use of an elemental analyzer (Elementar, Langenselbold, Germany). The combustion of samples was performed at 1200 °C. The measurements were conducted in two repetitions to obtain the average value, similar to previous cases.

2.2.4. Particle Size Distribution

The laser particle sizer (Fritsch, Idar-Oberstein Germany) with a measuring range from 0.01 µm to 3800 µm and highest accuracy was used to assess the particle size distribution of the sludge dust. The measurements were conducted in three repetitions.

2.2.5. Spontaneous Ignition Behavior

The self-ignition temperature (T_{SI}) of sludge dust and sludge pellets was determined as a function of volume by a hot storage experiment, according to EN 15188:2020 Determination of the spontaneous ignition behavior of dust accumulations.

In the work, the pseudo-Arrhenius empiric method of determining T_{SI} was used. In this method, the non-ignition and ignition regions are separated by the curve (3):

$$\frac{V}{A} = \alpha e^{\frac{\beta}{T}} \quad (3)$$

where $\frac{V}{A}$ is the ratio of volume to the area, T is temperature, e is the base of the natural logarithm, and α, β are fit constants. For the purpose of fitting, (3) was log-transformed to represent the form of the linear dependence of the logarithm of $\frac{V}{A}$ on inverse temperature. This approach was widely used in the investigations, according to EN 15188, as well as in research papers [33–36]. The fitting was conducted using the Python [37] Numpy polyfit routine [38].

Samples were filled into three mesh wire baskets with a volume of 21.21 cm^3 (this volume corresponds to the volume of a cylinder with a diameter equal to a height of 3 cm), 50.27 cm^3 (this volume corresponds to the volume of a cylinder with a diameter equal to a height of 4 cm), and 98.17 cm^3 (this volume corresponds to the volume of a cylinder with a diameter equal to a height of 5 cm), and were placed in the center of the furnace for the self-heating of solid materials (ANKO, Warszawa, Poland). The baskets of different volumes were used in order to carry out an assessment of the self-heating behavior of larger dust and pellet volumes by extrapolation. The measurements were taken until the highest furnace temperature, at which the dust did not ignite (T_{SI}), and the lowest furnace temperature, at which the dust ignited was determined with an accuracy of 2 °C [39].

3. Results and Discussion

3.1. Moisture Content Analysis

The results of the moisture content analysis are presented in Table 1. The sludge pellets had a higher average moisture content (9.974 ± 0.414%) compared to the sludge dust (6.067 ± 0.193%). However, it is still low in both materials and consistent with the thermal drying treatment. The moisture content of sewage sludge may vary from 5.60% to 79.54%. Dry sewage sludge is expected to be more reactive, because the steam may support the early production of highly reactive hydrogen and carbon monoxide via exothermic reforming [40].

Although water is one of the initiators of self-heating processes and is involved in exothermic processes, in which it can act as a reactant or oxygen carrier, on the other hand, its evaporation can act as a temperature regulator of the system [41].

3.2. Bulk Density Analysis

The results of the bulk density analysis are presented in Table 2.

Table 1. The moisture content analysis results.

Material	Drying Time [s]	Sample Mass		Moisture Content [%]	Average Moisture Content [%]
		Before Drying [g]	After Drying [g]		
Sludge dust	520	2.003	1.878	6.241	6.067 ± 0.193
	405	2.000	1.878	6.100	
	455	1.997	1.880	5.859	
Sludge pellets	960	2.001	1.801	9.995	9.974 ± 0.414
	1116	2.000	1.809	9.550	
	1266	2.004	1.796	10.378	

Table 2. The bulk density analysis results.

Material	Volume [cm^3]	Sample Mass [g]	Bulk Density [g/cm^3]	Average Bulk Density [g/cm^3]
Sludge dust	46	19.88	0.432	0.427 ± 0.008
	46	19.36	0.421	
Sludge pellets	50	30.91	0.618	0.621 ± 0.005
	50	31.18	0.623	
	50	31.32	0.626	
	50	30.81	0.616	

Pelletization enables the efficient handling and transportation of biomass. Besides obtaining a definite size and shape, densified biomass has a greater bulk density [42]. A significant increase in the average bulk density of sludge pellets (0.621 g/cm^3) was observed compared to sludge dust (0.427 g/cm^3). Schwarzer et al. [43] reported that the increase in the bulk density of biomass dust results in a reduction in the critical temperature. However, a greater influence on the self-ignition temperatures and the heat transfer within the particle bed is exerted by the sample size.

3.3. Elemental Analysis

The results of the elemental analysis are presented in Table 3. The elemental analysis showed that the carbon, hydrogen, nitrogen, and sulfur contents of the studied dried sludge were in the range of values of these components, according to the elemental analyses results of a few sewage sludges from different treatment facilities, included in the Environment Protection Agency (EPA) report [44]. However, only the carbon content was below the mean value (31.17%). The contents of hydrogen, nitrogen, and sulfur were higher than the mean values (3.94%, 3.84%, and 1.32%, respectively).

Table 3. The elemental analysis results.

Material	C [%]	H [%]	N [%]	S [%]
Sludge dust	26.84	4.581	5.20	1.581
	26.69	4.569	5.14	1.576
Average	26.77 ± 0.11	4.575 ± 0.008	5.17 ± 0.04	1.579 ± 0.004
Sludge pellets	30.66	5.272	4.79	1.580
	30.97	5.197	4.85	1.559
Average	30.82 ± 0.22	5.235 ± 0.053	4.82 ± 0.042	1.570 ± 0.015

The greatest difference was noted in the elemental content of carbon, which was 4.05% higher for the sludge pellets. A slightly higher hydrogen content of 0.66% was also assigned in the sludge pellets. The nitrogen ($5.17 \pm 0.04\%$) and the sulfur contents ($1.579 \pm 0.004\%$) were inconsiderably higher in the sludge dust compared to sludge pellets.

The hydrogen content is one of the parameters that influence the first stage of the self-heating process. The higher hydrogen content of sludge pellets results in a faster appearance of the initial exothermic reactions (slow oxidation). However, hydrogen is not the only element that affects self-heating behavior [6]. The sulfur content, which is marginally lower in the sludge pellets, increases flammability due to its oxidation tendency [45].

3.4. Particle Size Distribution Analysis

The results of the particle size distribution analysis, in terms of cumulative frequency, are presented in Tables 4–7. The frequency distribution and cumulative frequency of the particle size distribution of sludge dust are presented in Figures 1–3.

Table 4. Results of the first particle size distribution analysis in terms of cumulative frequency.

Particle Size [µm]	Sample 1 [%]	Sample 2 [%]	Sample 3 [%]	Average [%]	CV * [%]
<50	14.936	15.232	15.235	15.134	0.926
<70	23.109	23.503	23.516	23.376	0.807
<100	35.010	35.528	35.577	35.372	0.725
<150	51.791	52.348	52.488	52.209	0.577
<200	65.443	65.887	66.202	65.844	0.473
<275	81.204	81.457	81.990	81.550	0.401
<370	93.217	93.328	93.782	93.442	0.262
<520	99.421	99.439	99.526	99.462	0.046
<710	99.998	99.999	99.999	99.999	0
<1000	100	100	100	100	0
<1500	100	100	100	100	0
<2000	100	100	100	100	0

* CV—coefficient of variation.

Table 5. Results of the second particle size distribution analysis in terms of cumulative frequency.

Particle Size [µm]	Sample 1 [%]	Sample 2 [%]	Sample 3 [%]	Average [%]	CV * [%]
<50	17.511	17.291	17.686	17.496	0.924
<70	26.993	26.571	27.043	26.869	0.788
<100	40.031	39.226	39.855	39.704	0.870
<150	57.289	56.034	56.956	56.760	0.935
<200	70.461	69.225	70.057	69.914	0.736
<275	84.712	83.920	84.167	84.267	0.393
<370	94.852	94.547	94.379	94.593	0.207
<520	99.628	99.596	99.531	99.585	0.040
<710	99.999	99.999	99.999	99.999	0.000
<1000	100	100	100	100	0
<1500	100	100	100	100	0
<2000	100	100	100	100	0

* CV—coefficient of variation.

The particle size distribution analysis showed that the minimum particle size is 0.6 µm and the maximum is 720 µm. The particles in a size range of 710–1000 µm represent 0.013% of dust, which is the rarest frequency of particle sizes. The most frequent particle sizes are in the range of 100–150 µm (16,270%).

Particle size influences the self-ignition temperature. The decrease in the T_{SI} with the decrease in the particle size of the wheat biomass was observed by Restuccia et al. [46]. The results showed that the self-ignition temperature slightly decreases with the particle size. However, the higher bulk density of the sludge pellets may be a reason for the offsetting particle size effect due to the larger amount of fuel for a given basket volume.

Table 6. Results of the third particle size distribution analysis in terms of cumulative frequency.

Particle Size [μm]	Sample 1 [%]	Sample 2 [%]	Sample 3 [%]	Average [%]	CV * [%]
<50	13.294	13.410	13.637	13.447	1.060
<70	19.920	19.980	20.348	20.083	0.943
<100	29.883	29.856	30.389	30.043	0.817
<150	44.740	44.730	45.409	44.959	0.707
<200	57.548	57.562	58.421	57.844	0.706
<275	73.579	73.462	74.585	73.875	0.682
<370	87.918	87.646	88.721	88.095	0.518
<520	98.016	97.851	98.297	98.055	0.188
<710	99.961	99.951	99.976	99.963	0.010
<1000	100	100	100	100	0
<1500	100	100	100	100	0
<2000	100	100	100	100	0

* CV—coefficient of variation.

Table 7. The average particle size distribution analysis in terms of cumulative frequency.

Particle Size [μm]	Analysis 1 [%]	Analysis 2 [%]	Analysis 3 [%]	Average [%]	CV * [%]
<50	15.134	17.496	13.447	15.359	0.132
<70	23.376	26.869	20.083	23.443	0.145
<100	35.372	39.704	30.043	35.039	0.138
<150	52.209	56.760	44.959	51.309	0.116
<200	65.844	69.914	57.844	64.534	0.095
<275	81.550	84.267	73.875	79.897	0.067
<370	93.442	94.593	88.095	92.043	0.038
<520	99.462	99.585	98.055	99.034	0.009
<710	99.999	99.999	99.963	99.987	0
<1000	100	100	100	100	0
<1500	100	100	100	100	0
<2000	100	100	100	100	0

* CV—coefficient of variation.

3.5. The Spontaneous Ignition Behavior Analysis

The results of hot storage experiments for the sludge dust and sludge pellets are presented in Table 8. The induction time t_i, defined as the time between reaching the storage temperature and the start of ignition of a sample, was higher for the sludge pellets compared to sludge dust. The most significant value differences were observed for the sample baskets of the volume of 21.21 cm^3, 50.27 cm^3, and 98.17 cm^3. The self-ignition temperatures were also higher for the sludge pellets. The greatest increase in T_{SI} was observed for the sample basket of a volume of 21.21 cm^3, from 160 °C for the sludge dust to 186 °C for the sludge pellets.

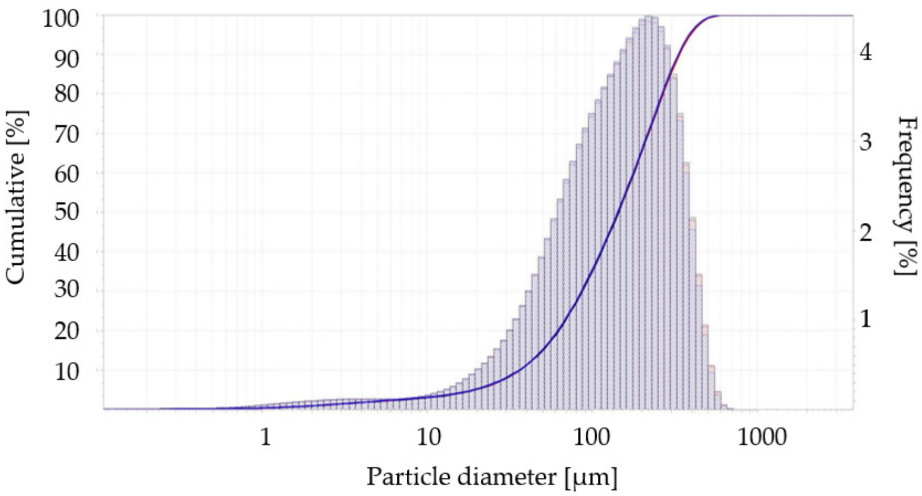


Figure 1. The frequency distribution and cumulative frequency of particle size distribution of sludge dust (measurement 1).

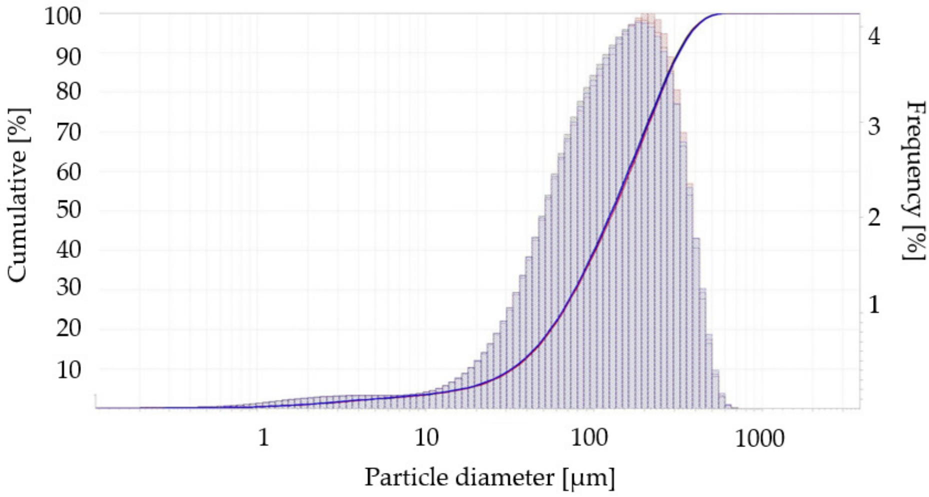


Figure 2. The frequency distribution and cumulative frequency of particle size distribution of sludge dust (measurement 2).

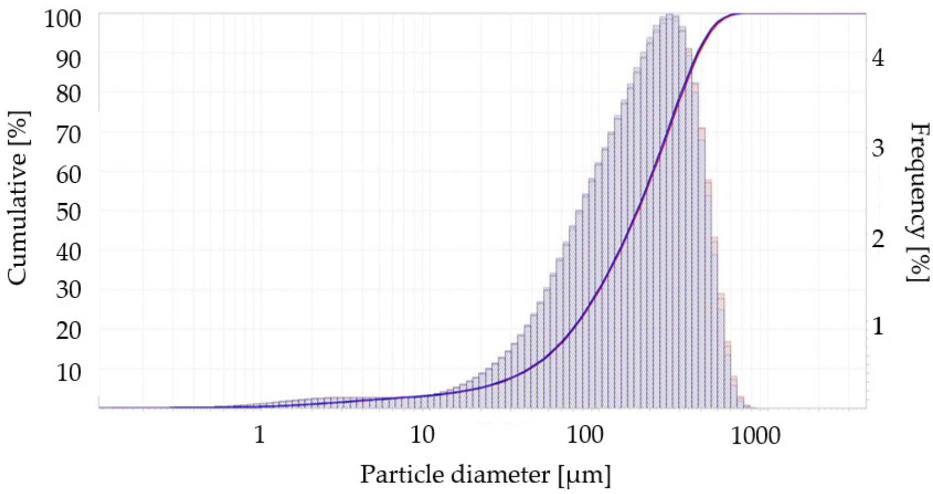
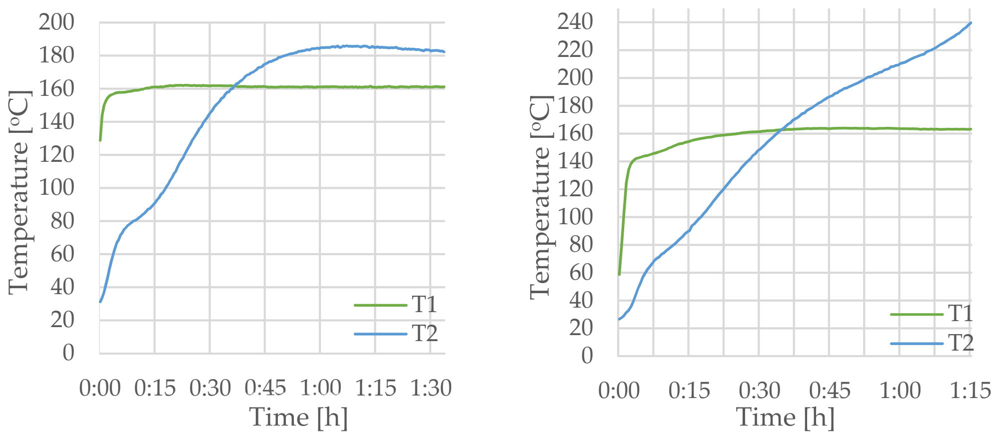


Figure 3. The frequency distribution and cumulative frequency of particle size distribution of sludge dust (measurement 3).

Table 8. The spontaneous ignition behavior analysis results.

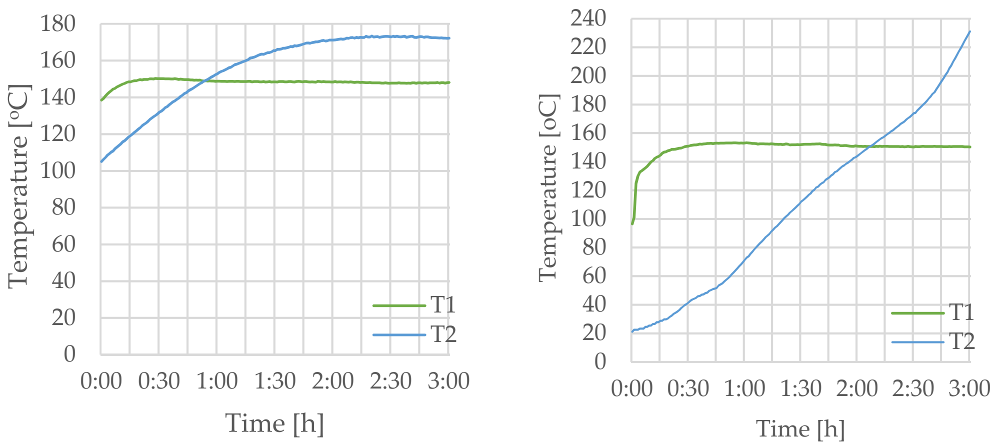
Material	Sample Basket	Corresponding Silos		Induction Time t_i [h:min:s]	Self-Ignition Temperature T_{SI} [°C]
	Volume [cm^3]	Diameter [cm]	Height [cm]		
Sludge dust	21.21	3	3	00:15:00	160
	50.27	4	4	00:57:51	148
	98.17	5	5	01:12:04	142
Sludge pellets	21.21	3	3	00:36:21	186
	50.27	4	4	01:06:00	172
	98.17	5	5	01:47:12	160

The temperature of sludge dust in different sample baskets and the furnace temperature are presented in Figures 4–9. The T1 curve stands for the furnace temperature and the T2 curve for the sample temperature.



(**a**) (**b**)

Figure 4. The temperature of sludge dust in a 21.21 cm^3 basket: (**a**) at a furnace temperature of 160 °C with no evidence of dust ignition, (**b**) at a furnace temperature of 162 °C with a dust ignition.



(**a**) (**b**)

Figure 5. The temperature of sludge dust in a 50.27 cm^3 basket: (**a**) at a furnace temperature of 148 °C with no evidence of dust ignition, (**b**) at a furnace temperature of 150 °C with a dust ignition.

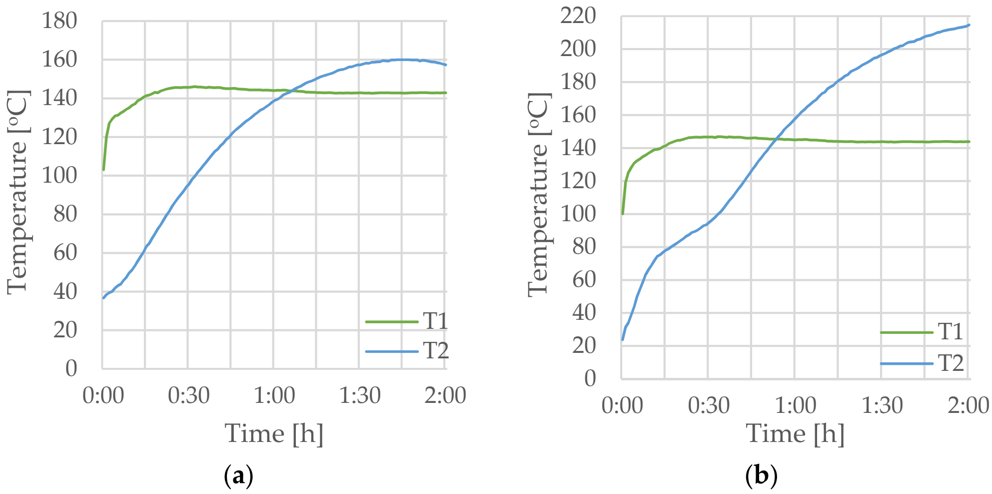


Figure 6. The temperature of sludge dust in a 98.17 cm^3 basket: (**a**) at a furnace temperature of 142 °C with no evidence of dust ignition, (**b**) at a furnace temperature of 144 °C with a dust ignition.

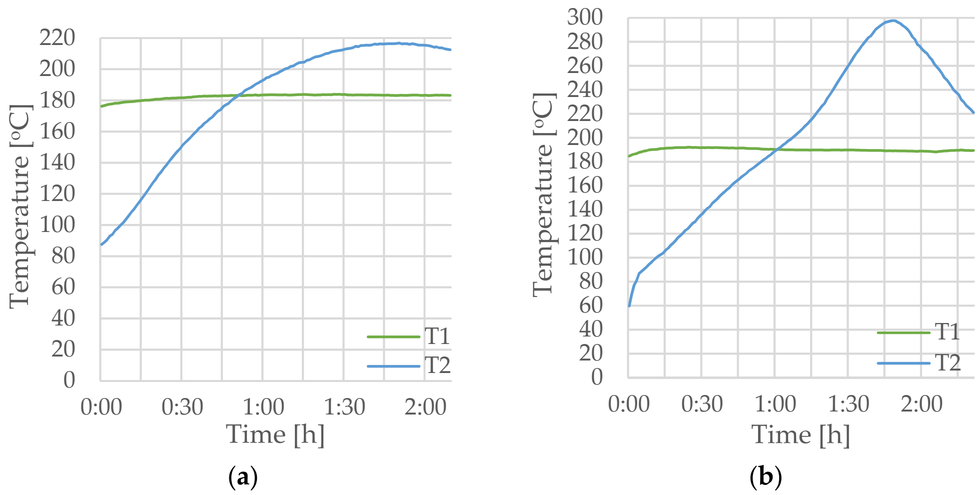


Figure 7. The temperature of sludge pellets in a 21.21 cm^3 basket: (**a**) at a furnace temperature of 186 °C with no evidence of dust ignition, (**b**) at a furnace temperature of 188 °C with a dust ignition.

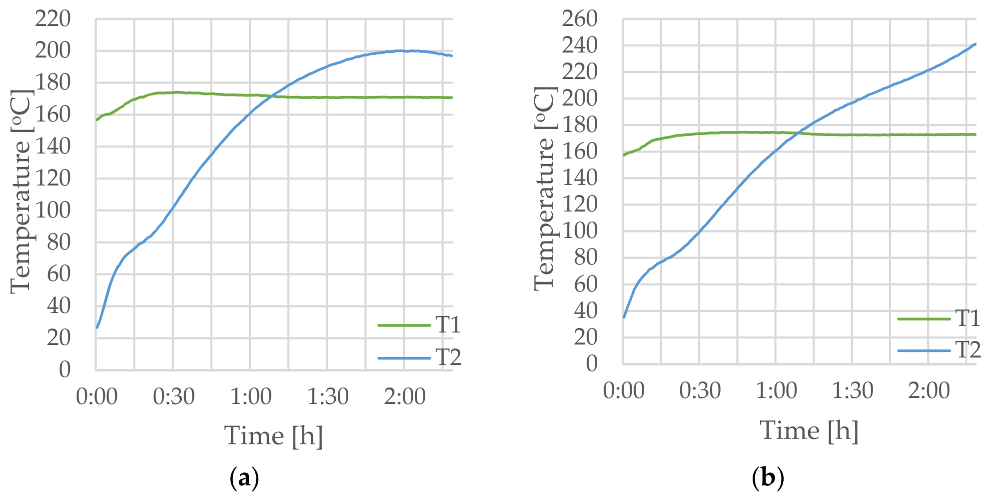


Figure 8. The temperature of sludge pellets in a 50.27 cm^3 basket: (**a**) at a furnace temperature of 170 °C with no evidence of dust ignition, (**b**) at a furnace temperature of 172 °C with a dust ignition.

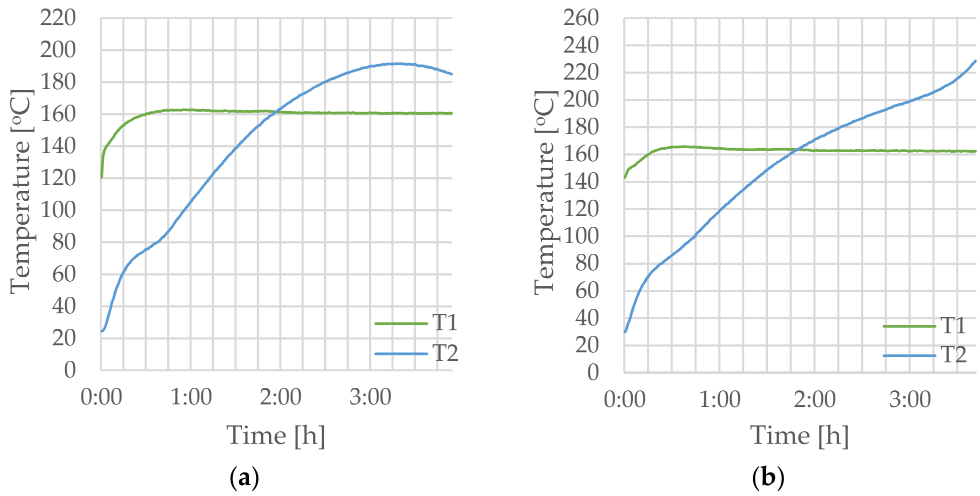


Figure 9. The temperature of sludge pellets in a 98.17 cm^3 basket: (**a**) at a furnace temperature of 160 °C with no evidence of dust ignition, (**b**) at a furnace temperature of 162 °C with a dust ignition.

The temperature of sludge pellets in different sample baskets and the furnace temperature are presented in Figures 7–9.

A pseudo-Arrhenius graph of the sludge-dust spontaneous-combustion temperatures is shown in Figure 10. A line through the T_{SI} values separates areas representing stable (below the line) and unstable (above the line) dust volume behavior. Self-ignition of the sludge dust occurs in the area above the line.

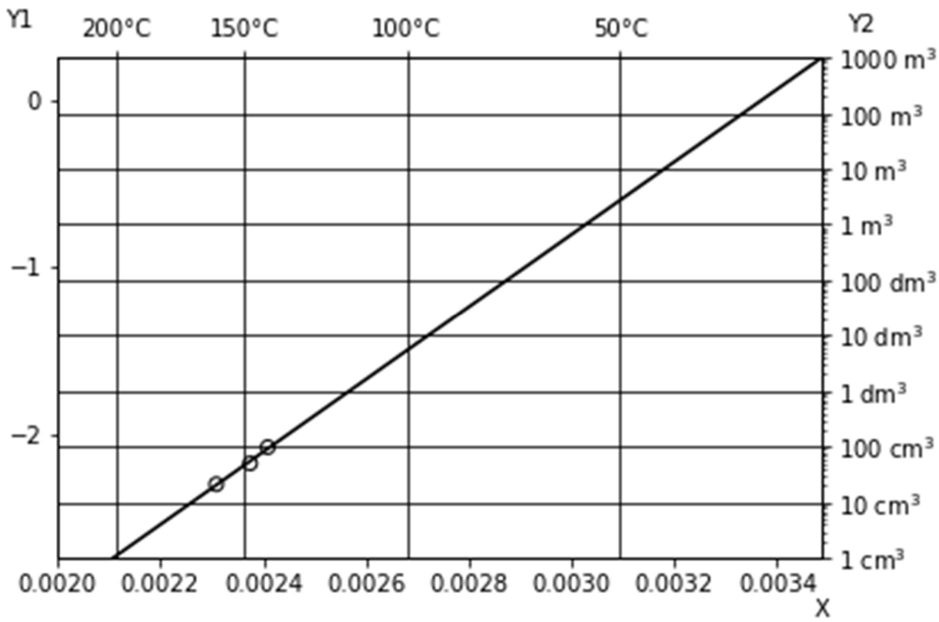


Figure 10. Pseudo-Arrhenius graph of the self-ignition temperature of the sludge dust.

The dependence of the induction time of the combustion (t_i) on the volume/surface ratio of the sludge dust is shown in Figure 11. It yields the determination of the time needed for a sample to undergo spontaneous combustion when stored at temperatures slightly higher than T_{SI} by an extrapolation method. A line through the t_i values separates areas representing stable (above the line) and unstable (below the line) dust behavior.

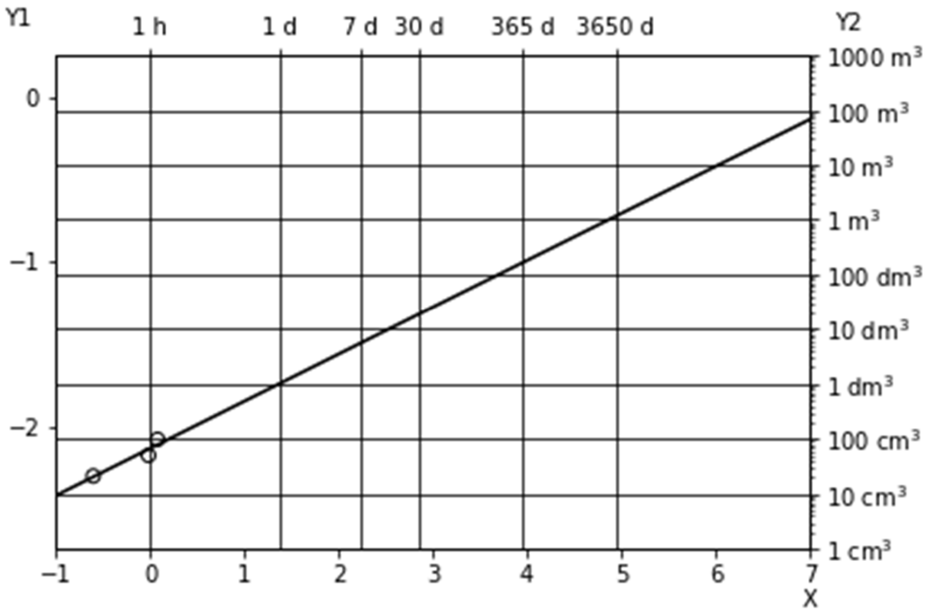


Figure 11. Dependence of the induction time of the combustion (t_i) on the volume/surface ratio of the sludge dust.

Big-bag-type containers (1 m^3), tank chambers (10 m^3), containers (45 m^3), and silo vehicles (60 m^3) are used for the storage and transport of sludge dust. The critical conditions are summarized in Table 9.

Table 9. The critical values of time and temperature for storage and transport of the sludge dust.

Material	Volume [m^3]	Temperature [°C]	Time [days]
Big-bag	1	88.3	63.6
Tank chamber	10	75.7	346
Container	45	68.9	1043
Silo vehicle	60	66.5	1289

A pseudo-Arrhenius graph of the sludge pellets' spontaneous combustion temperatures is shown in Figure 12.

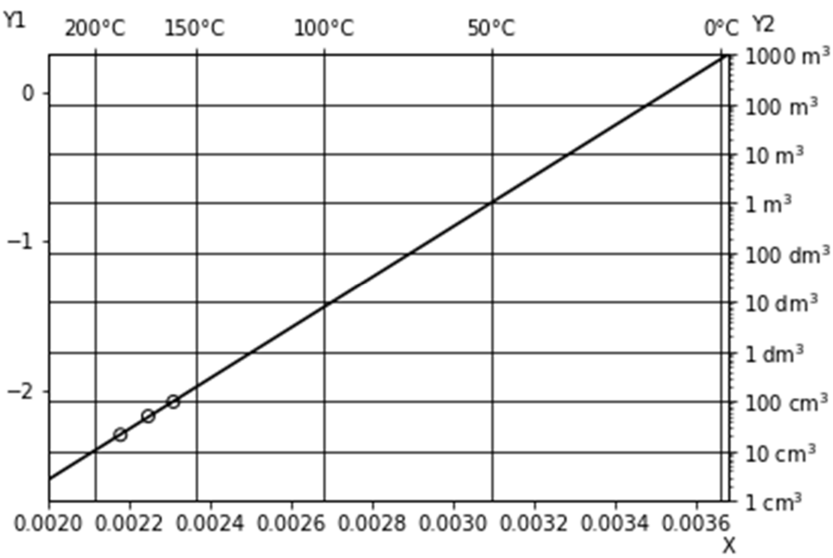


Figure 12. Pseudo-Arrhenius graph of the self-ignition temperature of the sludge pellets.

The dependence of the induction time of the combustion (t_i) on the volume/surface ratio of the sludge pellets is shown in Figure 13.

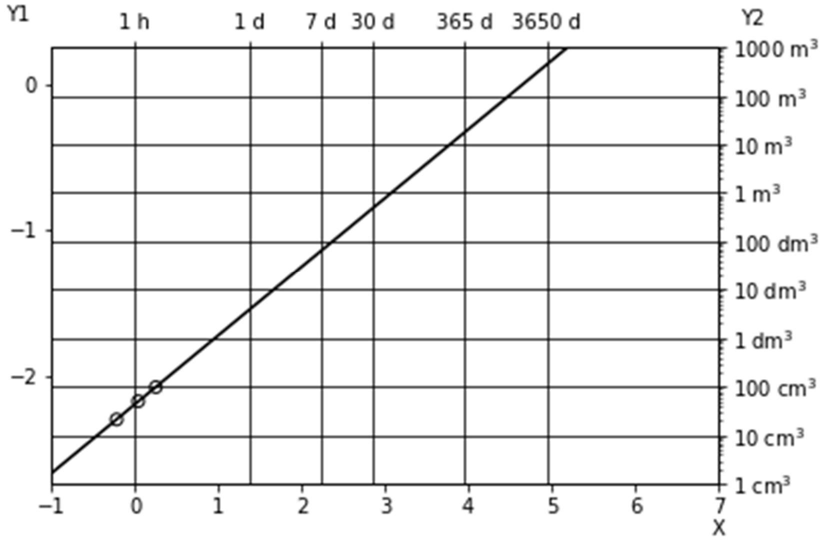


Figure 13. Dependence of the induction time of the combustion (t_i) on the volume/surface ratio of the sludge pellets.

The maximum volume of silo for the storage of sludge pellets is 100 m^3; thus, the critical values of the temperature and time are 13.8 °C and 1280 days, respectively.

The pseudo-Arrhenius plots of the self-ignition temperature for the sludge dust and sludge pellets show that the sludge in the form of pellets has more favorable storage conditions.

It is also associated with the particle size and the specific surface area. The sludge dust, as a finer material, is distinguished by the reduced mass and heat transfer through the bed, which results in the development of higher local temperatures. The higher the specific surface area of sludge dust, the greater surface exposed to the air, thus increasing the reaction rate. The intraparticle oxygen permeability may be reduced via pelletization, which may lower the hazard of self-heating [47].

4. Conclusions

The higher induction times and higher self-ignition temperatures of sludge pellets compared to sludge dust confirms that sludge after pelletization is safer for storage for long periods. The highest self-ignition temperatures were obtained for the smallest basket volume. For the sludge pellets, the value of 186 °C was achieved, whereas for the sludge dust, it was 26 °C lower. The obtained T_{SI} values decrease with the reduction in material volume and are the lowest for the highest basket volume (160 °C and 142 °C for the sludge pellets and sludge dust, respectively).

The moisture content of both dust and pellets is low. However, slightly higher results were obtained for the sludge pellets (9.974 ± 0.414%) compared to the sludge dust (6.067 ± 0.193%). The low moisture content and the small difference in these values indicate its negligible impact in consideration of both materials. Sludge pellets have a higher bulk density (0.621 ± 0.005 g/cm^3) compared to sludge dust (0.427 ± 0.008 g/cm^3). Apart from the positive influence on increasing the critical temperature, the higher bulk density of materials affects their storage and handling. The elemental analysis showed that the sludge dust has a higher hydrogen content (5.235 ± 0.053%) compared to sludge dust (4.575 ± 0.008%), which may result in a faster appearance of the initial exothermic reactions. The most frequent particle sizes of sludge dust are in the range of 100–150 µm, which are significantly lower than pellet size. Lower particle sizes have been shown to reduce self-ignition temperatures.

The obtained information on safe storage volumes, corresponding temperatures, and times revealed that, despite the sludge pellets being easier in terms storage and handling issues and having a more favorable particle size and bulk density, sludge dust is more favorable for the management of studied sewage sludge in terms of fire risk.

Further work on the impact of the pellet size, as well as ash content, would be of interest. Future research into the hazards of silo fires and explosions is needed to better understand the process of self-heating of dried sewage sludge. Silo fire prevention and management should also be a following area of research.

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