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Influence of Valorization of Sewage Sludge on Energy Consumption in the Drying Process

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Abstract: Valorization of digested sewage sludge generated in a medium-sized sewage treatment plant and the effect of valorization on energy consumption during sludge drying used for energy recovery are presented. Anaerobic digestion of sewage sludge reduces dry matter content compared to raw sludge. This lowers its calorific value leading to the lower interest of consumers in using it as fuel. The aim of the study was to valorize digested sewage sludge prior to drying with high-energy waste with low moisture content. The procedure led to the reduction in moisture content by about 50% in the substrate supplied for solidification and drying. The calorific value of digested sewage sludge increased by 50–80%, and the energy consumption of the drying process decreased by about 50%. Physical and chemical properties of sewage sludge and moisture content of substrates and mixtures after valorization were determined. The heat of combustion of valorized sewage sludge mixtures, their elemental composition, and ash content is investigated. Their calorific value in the analytical and working states of 10% H_2O was calculated. The highest calorific value was obtained for the mixture of sewage sludge valorized with waste plastics or combined with wood dust, averaging 23 MJ/kg. A mathematical approximation of sewage sludge valorization is presented.

Keywords: sewage sludge; organic matter; valorization; energy saving; alternative fuel

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1. Introduction

Municipal sewage sludge is a by-product of the treatment of municipal and industrial wastewater [1,2]. Sewage sludge constitutes only 1–2 vol.% of treated wastewater, but its management is very complicated, and treatment costs amount to 20–60% of wastewater treatment plants' (WWTPs') total operating costs [3]. Sewage sludge from sewage treatment plants (STPs) is characterized by a high content of organic and inorganic substances, including microbial biomass, pathogens, nutrients N and P, and metals. In addition, they have a very heterogeneous composition [4] and a high water content up to 95–99% [5]. The water content varies according to the type of sewage sludge (Table 1).

Table 1. The content of water in sewage sludge according to different authors.

Content of Water	Raw Sludge	Thickened Sewage Sludge	Digested and Dewatered Sewage Sludge		
			Centrifuge	Belt Filter Press	Chamber Filter Press
(%)	99–95	95–90	80–78	75–70	70–68
Ref.	[5]	[6]	[7]	[8]	[9]

Sewage sludge is one of the substances that are difficult to dewater. Without pretreatment, the dewatering effects and separation rates of sewage sludge are very low [10]. High-molecular-weight polyelectrolytes are most commonly used for conditioning. Their consumption depends on the dewatering equipment used and amounts to 5–12 g/kg d.m. [11].

Sludge treatment in large and medium sewage treatment plants includes such processes as thickening, anaerobic stabilization, mechanical dewatering, and drying. Anaerobic stabilization (methane production) changes the properties of sewage sludge. In this process, ca. 50% of the organic matter contained in the water is decomposed. Each kilogram of decomposed organic matter can yield 0.49–0.75 Nm^3/kg d.m. of biogas [12,13]. The gas produced in the process lowers the calorific value of the sludge by approximately 2–4 MJ/kg (Figure 1) [9,12].

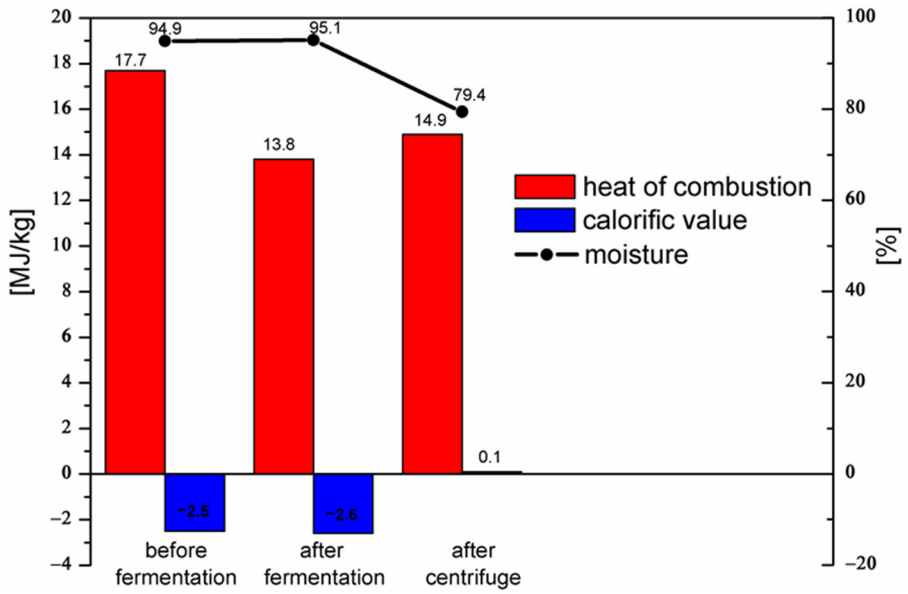


Figure 1. Heat of combustion, calorific value, and moisture of sewage sludge.

Water content in sewage sludge after digestion and dewatering is 68–80% H_2O. The content of heavy metals in the sludge increases [14,15]. Siebielec and Stuczyński [16] studied sewage sludge from 43 wastewater treatment plants in Poland and presented statistical analyzes of the results (Table 2). The authors showed a large variation in the content of heavy metals in sewage sludge. The content of cadmium, chromium, and nickel was the most variable in the tested samples. According to the authors, it is related to the runoff of surface water to the sewage system from metallurgical waste dumps, which are located in the vicinity of the sewage treatment plant.

Table 2. The range and coefficients of variation of selected parameters of sewage sludge [16].

Parameter	Average (Median)	Range	Coefficient of Variation, %
Organic matter, %	42.2 (43.3)	13.6–65.1	33
Nitrogen, %	2.61 (2.48)	0.55–5.64	49
Phosphorus, %	1.83 (1.75)	0.14–4.08	47
Potassium, %	0.25 (0.21)	0.09–0.87	57
Calcium, %	3.93 (3.82)	0.81–19.9	62
Magnesium, %	0.58 (0.55)	0.01–1.7	73
Cu, mg/kg d.m.	184 (154)	41–449	55
Zn, mg/kg d.m.	2135 (1760)	541–9824	68
Cd, mg/kg d.m.	10.5 (4.95)	1.1–149.1	198
Ni, mg/kg d.m.	69.2 (39.1)	18–1172	214
Pb, mg/kg d.m.	173 (132)	45–953	85
Cr, mg/kg d.m	320 (69.9)	24–7544	315

Polycyclic aromatic hydrocarbons (PAHs), which have an affinity for solid sludge particulate matter, are accumulated in sewage sludge [17]. Contamination of sludge with PAHs was confirmed for both raw and digested sludge [18–20]. The development

of analytical techniques has led to the emergence of new problems concerning the use of sewage sludge in agriculture and nature, as new contaminants such as hormones, drug residues, flame retardants, and increased amounts of organic pollutants have been identified [21]. There is an ongoing discussion in EU countries regarding the maximum amounts of residual polymers in sewage sludge. This is planned to be taken into account when new legislation on sewage sludge management is drafted.

Sewage sludge contaminated with heavy metals, xenobiotics, and synthetic polymers cannot be used in agriculture or nature. The presence of these contaminants in sewage sludge represents a potential source of contamination of soils and waters. There is growing skepticism in the wider public about the use of sewage sludge in agriculture and soil reclamation [22].

Attempts have been made to use sewage sludge in the production of construction materials [23,24]. Rezaee et al. [25] showed that sewage sludge can be used up to 15% in the production of eco-cement, which has mineral components similar to traditional Portland cement. These applications offer alternative methods for sludge recycling, but the amounts of sludge used are only a small fraction of total sludge production, while sludge-based production is generally of lower quality and causes environmental concerns such as leaching of heavy metals [5].

Therefore, a sludge treatment scheme consisting of such processes as thickening, dewatering, drying, and energy recovery is enforced. A product obtained by drying sewage sludge can be used in thermal processes that allow energy recovery [26].

The energy consumption of drying depends mostly on the water content of sewage sludge and its structure. In sludge with very high water content, the amount of energy required to dry it may exceed the amount of energy recovered during thermal use. According to the work of [9], 60–70% more energy is needed to dry 1 Mg of sewage sludge containing 20% to 90% d.m. than to dry sludge containing 35% to 90% d.m. The theoretical energy requirement needed to evaporate 1 kg H_2O at normal pressure is 0.627 kW/kg H_2O. Depending on design solutions and installation parameters, the average energy demand is 0.6–1.2 kW/kg [27]. Lossman [28] presented a comparison of the energy intensity of sludge drying equipment derived from laboratory tests, with heat consumption coefficients higher than the values presented by Fukas-Płonka and Janik [27] (Table 3). According to the work of [29], the consumption of thermal energy for drying of sewage sludge in order to obtain the appropriate fuel-grade quality is between 1.8 and 2.2 kWh_{th}/kg_{DM}. Additionally, the electricity consumption of the drying equipment is between 0.10 and 0.30 kWh_{el}/kg_{DM}. The authors state that there is questionable energy efficiency between recovery of waste heat from sewage sludge incineration and thermal drying.

Table 3. Energy consumption of sewage sludge dryers.

Energy Consumption	Drum Dryer (DDS)	Belt Dryer (BDS)	Fluidized Bed Dryer (FDS)	Solar Dryer with Underfloor Heating
kW/kg H_2O	1.4–1.6	1.45 [1]–1.75	1.2	1.6

[1] with recuperation of heat.

Waste transformed into products that can be used for energy purposes is referred to as alternative or secondary fuel. It is produced by separating combustible fractions in the processes of sorting, multi-stage crushing, homogenization, and briquetting. The composition of the components that form an alternative fuel varies. They affect the final parameters such as lower heating value (LHV), moisture content, and ash content (Table 4).

Variable properties of secondary fuels reduce their use for energy production. Recipients of such fuels prefer fuels with unchanging parameters, as required by power equipment.

Table 4. Parameters of alternative fuels according to different authors.

LHV, MJ/kg	17.0	21.2	15.0	19.8
Moisture content, %	19.2	15.0	12.0	0.0
Ash content, %	11.0	10.9	16.0	3.4
Ref.	[30]	[31]	[32]	[33]

The paper presents research aimed at reducing the amount of energy needed to dry digested sewage sludge. The aim was achieved by the valorization of the sewage sludge before the actual drying. Waste of vegetable origins such as waste paper, wood dust, and plastic waste was used. Waste materials are characterized by low moisture content and calorific values higher than digested sludge. The resulting mixtures are characterized by plastic consistency, which enables briquetting or pelletizing of the final product. The valorization of sewage sludge offers substantial advantages: it increases the dry matter content of the sludge to be dried and at the same time reduces the energy consumption required for drying, increases the calorific value of the sludge, and contributes to an improvement in the CO_2 emissions toward minimum values. Borzooei et al. [34] showed research on the reduction in carbon footprint in a wastewater treatment plant. They have made an assessment of dynamic sludge thickener, as well as hybrid thermo-alkali pretreatment of waste-activated sludge to enhance the biogas production in the WWTP. To upgrade the produced biogas in sludge treatment units to biomethane with an average efficiency of 98.6%, the selective membranes were studied. The authors also proposed experimental microalgae technology for CO_2 fixation, which significantly reduces the carbon footprint of the wastewater treatment plant.

It is assumed that during the combustion, the amount of CO_2 emitted into the atmosphere equals the amount of the gas absorbed from the environment by the plant material (wood dust, waste paper).

In the present study, it was important to develop a method enabling quantitative and qualitative optimization of fuel components. This will allow for the production of goods with the assumed stable quality parameters, which is possible based on rational fuel valorization using analytical methods.

2. Materials and Methods

2.1. Characterization of Sewage Sludge

Digested sewage sludge (SS) generated in a Warta Sewage Treatment Plant in Częstochowa with a capacity of 46,000 m^3/d was used in the study. The wastewater treatment plant uses the activated sludge method with nitrification, denitrification, dephosphatation, and stabilization by methane fermentation. Stabilized sludge is mechanically dewatered on a belt press. Sludge samples were placed in sealed containers. The moisture content was measured three times, and the content of heavy metals was determined in the examined sludge. The particular physical and chemical analyses were carried out as follows:

- The moisture content of the hydrated sludge was measured using a Radwag HAC 110/NH weighing machine with a reading accuracy of 0.001%;
- Analysis of heavy metals was performed by the emission spectroscopy method with inductively coupled plasma (ICP-OES SPECTRO ARCOS). For this purpose, part of the sewage sludge was dried at 105 °C to a constant mass, ground in a ring mill, and mineralized with aqua regia (mineralization time 2 h, temperature 120 °C).

2.2. Sewage Sludge Valorization

Hydrated sewage sludge (SS) samples were used for valorization examinations. The sludge was valorized with waste paper (P), wood dust (D), and mixed waste plastics of polyethylene terephthalate and polypropylene (PPT). Polyvinyl alcohol PVA and calcium oxide CaO were used as binding additives. A total of 13 mixtures consisting of sewage sludge and selected wastes in appropriate proportions were prepared. Waste paper and

waste plastics were shredded before valorization. Mixing was performed in a ribbon mixer. The particular physical and chemical analyses were carried out as follows:

- The moisture contents of waste paper, plastics, and wood dust and mixtures were measured using a Radwag HAC 110/NH moisture analyzer with a reading accuracy of 0.001%. Then, the mixtures were placed in a steel die and pressed under pressure. A total of 13 briquette samples were obtained;
- Solidification of samples in the form of briquettes was carried out on a hydraulic press 250 C Żywiec, using pressures of 100 and 150 MPa;
- Elemental analysis of selected briquettes (C, H, N, S) was performed using a LECO TruSpec CHNS analyzer;
- The higher heating value (HHV) was determined in an IKA C2000 Basic isoperibolic calorimeter;
- The lower heating value (LHV) was calculated using the Boie formula [35];
- The bulk density of selected briquettes was determined according to the work of [36]. The mass of individual briquettes was determined using a laboratory balance. The volume was determined by a geometric method by measuring the diameter and height of cylindrical briquettes. The volume calculation was performed using the formula: Volume = Π·(briquette radius)^2·height. The bulk density of the briquette was calculated according to the formula: Bulk density = mass of briquette/volume of briquette. Ash content was determined according to the work of [37].

2.3. Approximation of Sewage Sludge Valorization

Taking into account the percentages of components in the 13 tested samples and the calculated calorific values, the mean square approximation of the data set was determined. For this, the following linear multivariable function is proposed:

$$z_{approx} = F(u_1, u_2, \ldots, u_k, p_1, p_2, \ldots, p_k) := \sum_{l=1}^{k} p_l u_l = p_1 u_1 + p_2 u_2 + \ldots + p_k u_k, \quad (1)$$

in which the coefficients p_l, $l = 1, 2 \ldots, k$, are the parameters of the function searched for, and the variables u_l, $l = 1, 2, \ldots, k$, are the arguments of the function. In order to determine the values of the coefficients, the least-squares criterion is defined, which takes the form:

$$S(p_1, p_2, \ldots, p_k) = \sum_{i=1}^{n} \left(\sum_{l=1}^{k} p_l \cdot (u_l)_i - z_i \right)^2 = \min, \quad (2)$$

The partial derivatives of the function S with respect to the particular parameters p_l, $l = 1, 2 \ldots, k$ are:

$$\frac{\partial S(p_1, p_2, \ldots, p_k)}{\partial p_j} = 2 \sum_{i=1}^{n} \left(\sum_{l=1}^{k} p_l \cdot (u_l)_i - z_i \right) (u_j)_i \quad (3)$$

The necessary condition for the existence of an extreme of a multivariable function leads to a linear system of equations in the form:

$$\sum_{i=1}^{n} \left(\sum_{l=1}^{k} p_l \cdot (u_l)_i - z_i \right) (u_j)_i = 0 \text{ for } j = 1, 2, \ldots, k, \quad (4)$$

And after its transformation, we obtain the following form:

$$\sum_{l=1}^{k} p_l \sum_{i=1}^{n} (u_l)_i (u_j)_i = \sum_{i=1}^{n} z_i (u_j)_i \text{ for } j = 1, 2, \ldots, k, \quad (5)$$

The above system of equation can also be written in the matrix form:

$$\mathbf{U} \cdot \mathbf{P} = \mathbf{Z}, \tag{6}$$

where

$$\mathbf{U} = \begin{bmatrix} \sum_{i=1}^{n} (u_1)_i (u_1)_i & \sum_{i=1}^{n} (u_2)_i (u_1)_i & \cdots & \sum_{i=1}^{n} (u_k)_i (u_1)_i \\ \sum_{i=1}^{n} (u_1)_i (u_2)_i & \sum_{i=1}^{n} (u_2)_i (u_2)_i & \cdots & \sum_{i=1}^{n} (u_k)_i (u_2)_i \\ \vdots & \vdots & \ddots & \vdots \\ \sum_{i=1}^{n} (u_1)_i (u_k)_i & \sum_{i=1}^{n} (u_2)_i (u_k)_i & \cdots & \sum_{i=1}^{n} (u_k)_i (u_k)_i \end{bmatrix}, \mathbf{P} = \begin{bmatrix} p_1 \\ p_2 \\ \vdots \\ p_k \end{bmatrix}, \mathbf{Z} = \begin{bmatrix} \sum_{i=1}^{n} z_i (u_1)_i \\ \sum_{i=1}^{n} z_i (u_2)_i \\ \vdots \\ \sum_{i=1}^{n} z_i (u_k)_i \end{bmatrix} \tag{7}$$

From the solution of the system of equations (6) $\mathbf{P} = \mathbf{U}^{-1} \cdot \mathbf{Z}$, we obtain the values of parameters p_1, $l = 1, 2 \ldots, k$. The determined parameters p_l allow us to determine the calorific value for any share of particular components of the sample using the approximation Formula (1) [38].

3. Results and Discussion

3.1. Characterization of Sewage Sludge

The main component of sewage sludge is dry organic matter, which constitutes over 64% (Table 5). The sludge is characterized by a high water content of above 77%. The high content of biogenic elements indicates the predominance of municipal sewage inflow to the treatment plant. The presence of heavy metals with the highest fraction of zinc also indicates the content of industrial sewage in the stream flowing into the treatment plant.

Table 5. Characterization of sewage sludge (SS).

Parameter	Unit	Value
Cd	mg/kg d.m.	8.0
Ni	mg/kg d.m.	111.0
Cu	mg/kg d.m.	254.0
Cr	mg/kg d.m.	405.0
Pb	mg/kg d.m.	101.0
Zn	mg/kg d.m.	2950.0
Co	mg/kg d.m.	4.8
K	mg/kg d.m.	2835.0
P	mg/kg d.m.	3.15
C	mg/kg d.m.	40.0
H	mg/kg d.m.	5.0
Organic matter	%	64.5
Mineral matter	%	35.5
Moisture content	%	77.26

The high water content hinders the efficient energy recovery from sewage sludge, which lowers its calorific value [39]. It is important that the sewage sludge sent for drying should have the highest possible dry matter content. In practice, treatment plants use equipment with low dewatering efficiency (centrifuges, belt presses), with a water content of sludge after dewatering of 70–80%. Consequently, sludge with high water content is sent for drying. The removal of 700–800 kg H_2O from 1 Mg of sewage sludge generates 30–50% of the costs incurred by the treatment plant. Drying sewage sludge is an energy-intensive process, which, with the expected increase in energy consumption, will result in higher prices for water supply and sewage treatment for both individual and business customers.

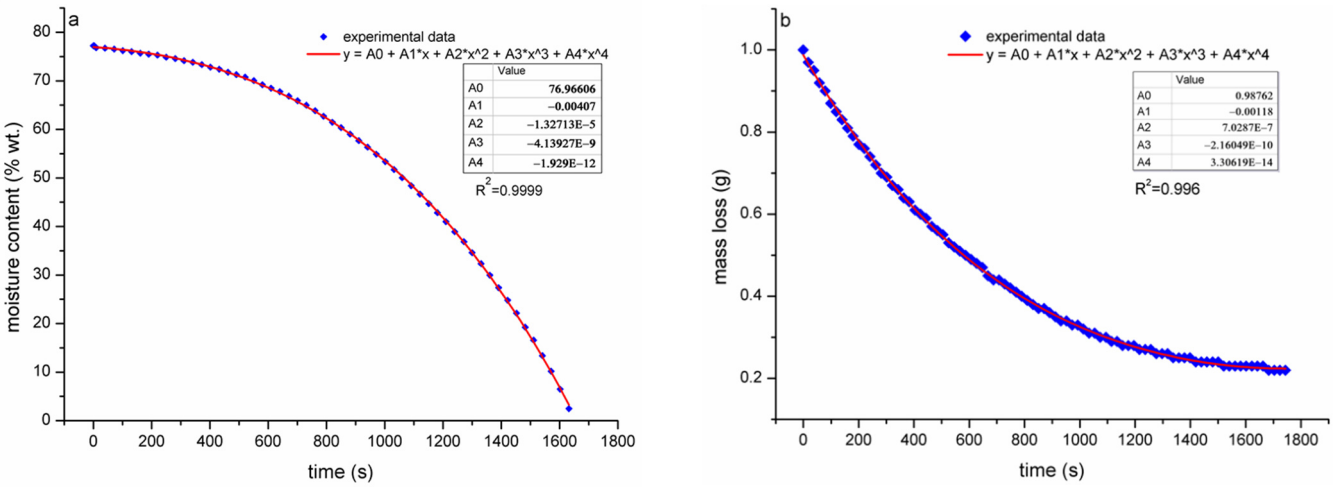
3.2. Sewage Sludge Valorization

The purpose of the valorization of digested sewage sludge was to reduce its moisture content and increase its calorific value. The waste selected for this purpose, i.e., waste

paper (P), wood dust (W), and waste plastics (PPT), is characterized by low moisture content and calorific value higher than in sewage sludge (Table 6). The range of calorific value for individual substrates is, respectively: for wood dust 17 MJ/kg [40], waste paper 11–26 MJ/kg, waste plastics 35 MJ/kg on average [41], sewage sludge 9–13 MJ/kg [42]. The change in the structure of sewage sludge resulting from the valorization made it possible to obtain mixtures of appropriate consistency, facilitating the solidification of briquettes. The results of the substrate moisture content measurements are shown in Figures 2–5.

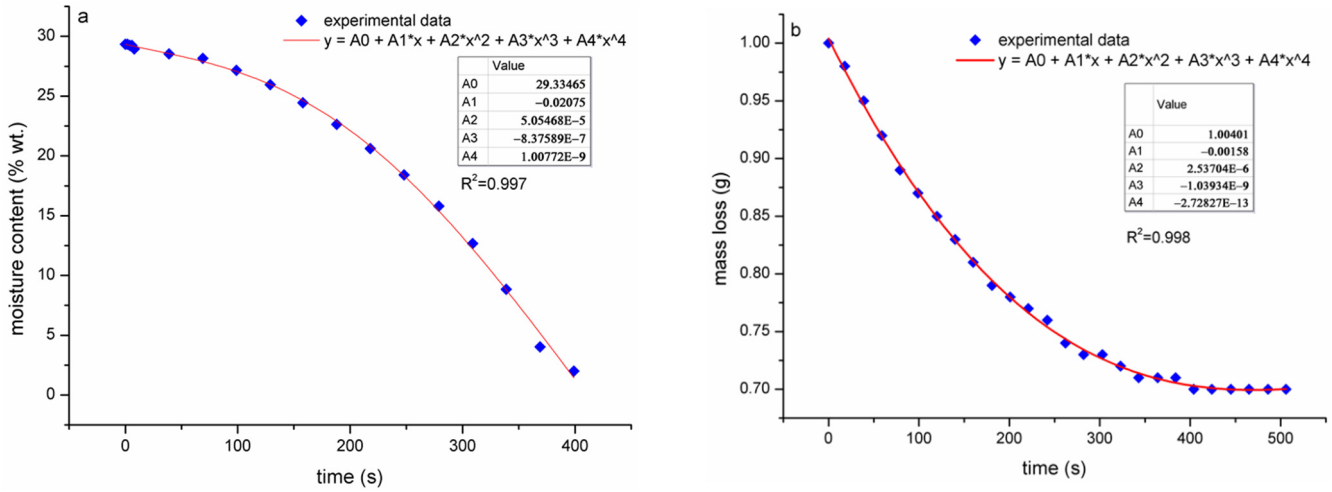
Table 6. Moisture content of the substrates.

Substrates	Moisture Content, %
Sewage sludge (SS)	77.26
Wood dust (D)	6.82
Waste paper (P)	6.58
Waste plastics (PPT)	29.80



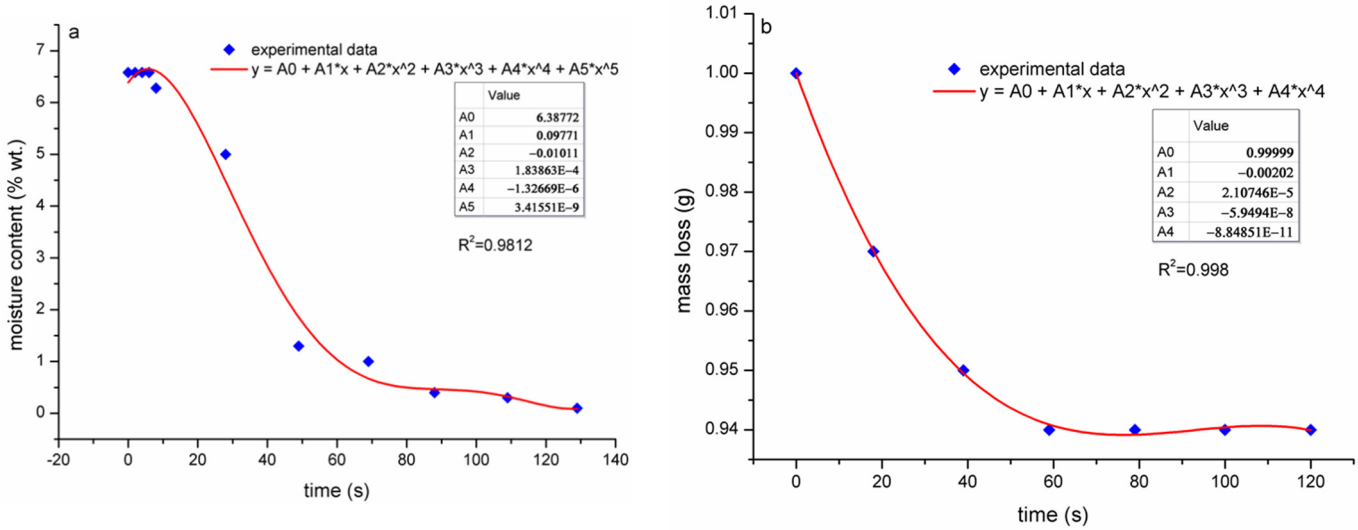
(**a**) (**b**)

Figure 2. Relation between: (**a**) moisture content over time of SS; (**b**) mass loss over time of SS.



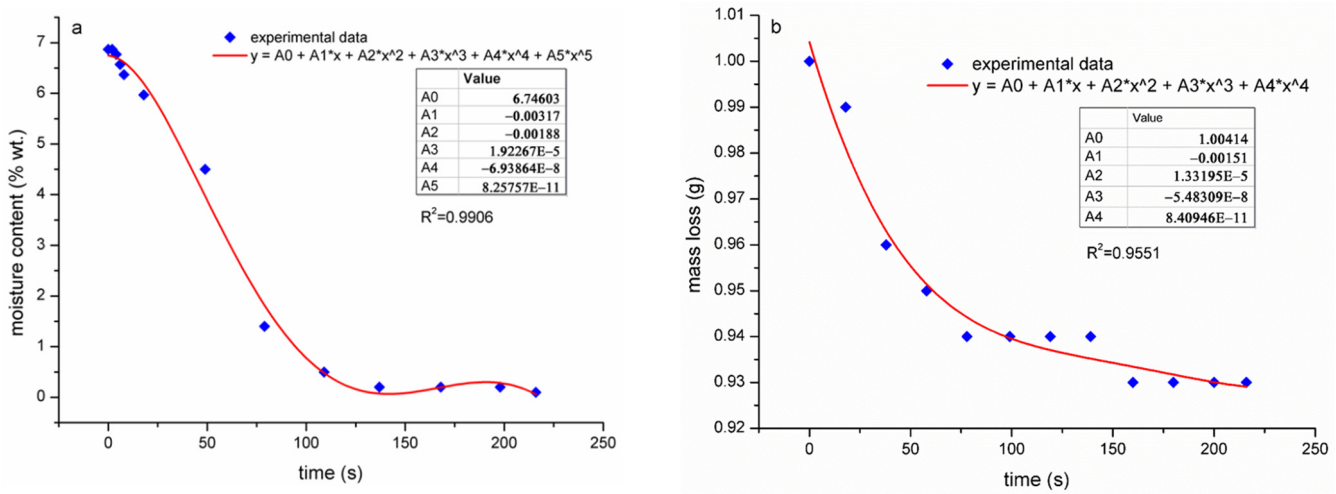
(**a**) (**b**)

Figure 3. Relation between: (**a**) moisture content over time of PPT; (**b**) mass loss over time of PPT.



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

Figure 4. Relation between: (**a**) moisture content over time of P; (**b**) mass loss over time of P.



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

Figure 5. Relation between: (**a**) moisture content over time of D; (**b**) mass loss over time of D.

The moisture content is 10 times lower in wood dust and waste paper and 2.6 times lower in waste plastics with respect to sewage sludge (Table 6). Drying of sewage sludge with a moisture content of 77.26% to analytical moisture took 1600 s. It took four times less time to dry PPT waste plastics (400 s) and 10 times less time to dry wood dust and waste paper (140 and 115 s, respectively). Therefore, it was assumed that the valorization of sewage sludge with these substrates would reduce its moisture content and drying time, thus contributing to a reduction in energy consumption. Thirteen mixtures were obtained as a result of valorization of sewage sludge with waste paper, wood dust, waste plastics, and PVA and CaO binding additives, with their composition and moisture content presented in Table 7.

Table 7. Composition and moisture content of the samples.

No	Mixture	Moisture Content (%)	Composition of the Mixtures, %wt.				
			Sewage Sludge (SS)	Wood Dust (D)	Waste Paper (P)	Waste Plastics (PPT)	PVA CaO (+)
1	SSD	42.04	50.0	50.0	-	-	-
2	SSD1+	41.20	49.0	49.0	-		2.0
3	SSD2+	35.57	41.0	57.0	-	-	2.0
4	SSD3+	32.75	37.0	61.0	-	-	2.0
5	SSP1	51.10	63.0	-	37.0	-	-
6	SSP2	41.92	50.0	-	50.0	-	-
7	SSP1+	50.27	62.0	-	36.0	-	2.0
8	SSP2+	41.08	49.0	-	49.0	-	2.0
9	SSP3+	33.31	38.0	-	60.0	-	2.0
10	SSPPT	53.52	50.0	-	-	50.0	-
11	SSPPTD	37.93	33.3	33.3	-	33.3	-
12	SSPPT+	52.46	49.0	-	-	49.0	2.0
13	SSPPTD+	37.16	32.7	32.7	-	32.7	2.0

The moisture content data for mixtures 1–13 indicate that this content in sewage sludge may be altered by valorization with other types of low-moisture waste. The proportions of low-moisture waste had a significant effect on the moisture content. The higher the content of low-moisture waste, the lower the moisture content of the resulting mixture (Figures 6–8). The lowest moisture content was found for SSD2+ and SSD3+ mixtures, whereas its highest values were observed in SSP1+, SSPPT, SSPPT+, and SSP1. The presence of binders in the mixtures has no significant effect on their moisture content (Table 7).

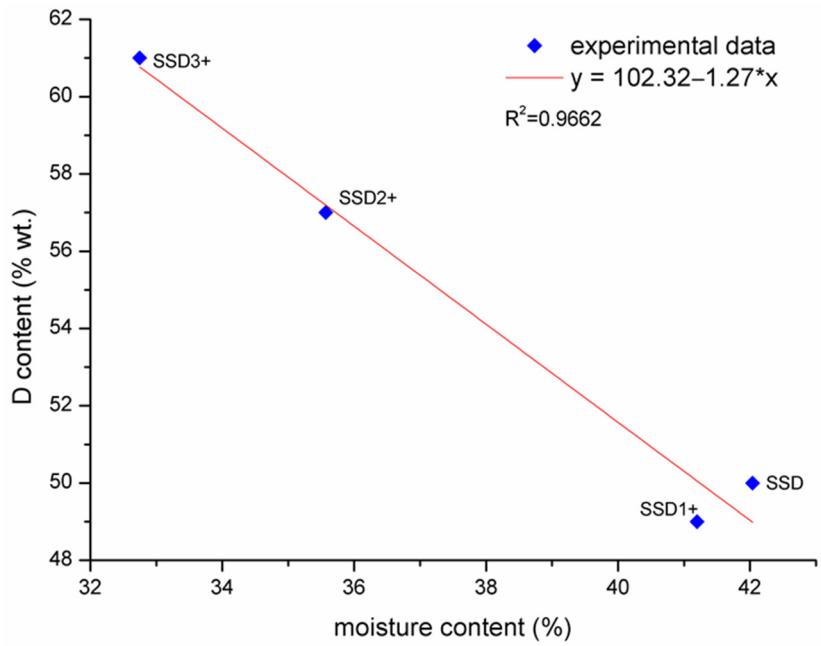


Figure 6. Correlation between percentage of D and moisture content for SSD, SSD1+, SSD2+, and SSD3+.

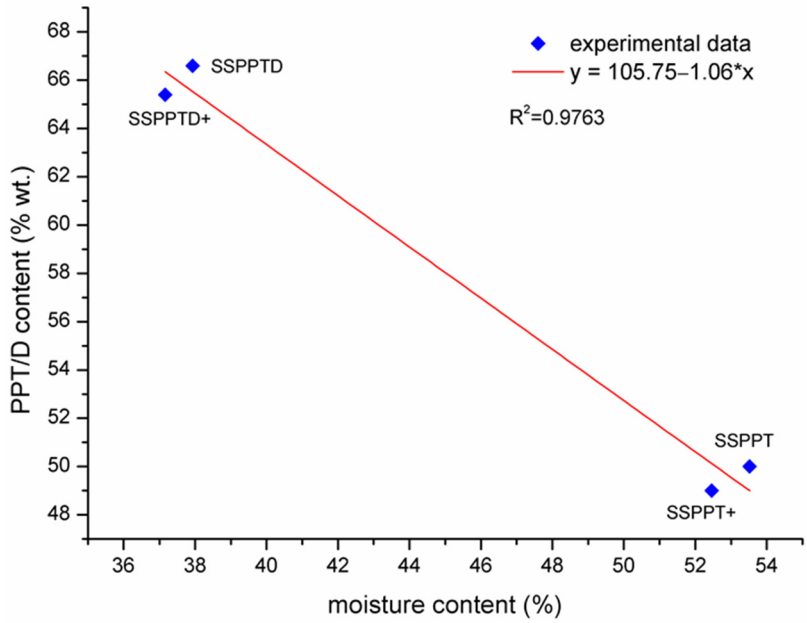


Figure 7. Correlation between percentage of PPT/D and moisture content for SSPPTD, SSPPTD+, SSPPT, and SSPPT+.

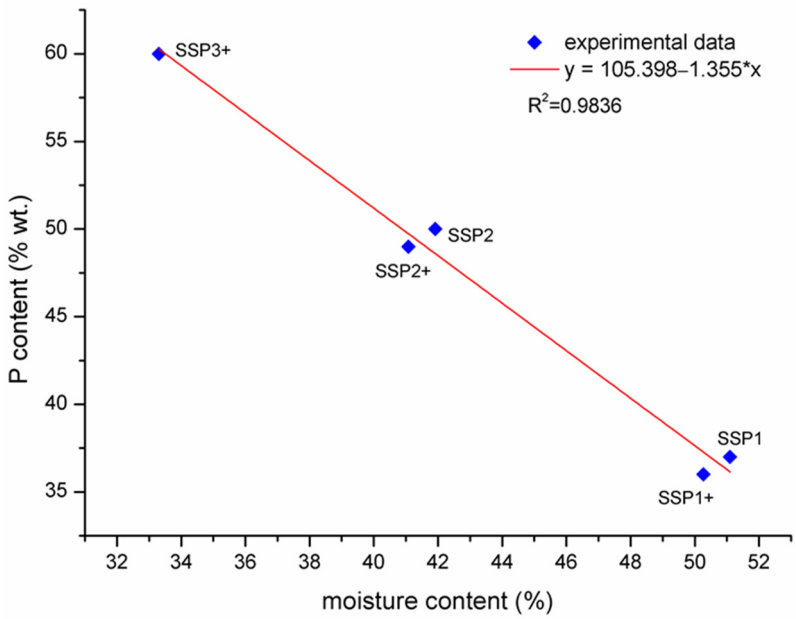


Figure 8. Correlation between percentage of P and moisture content for SSP1, SSP2, SSP1+, SSP2+, and SSP3+.

Mixtures with a similar moisture content of 37–41% were selected for further studies: SSD1+, SSP2+, and SSPPTD+. These mixtures are characterized by a low bulk weight of 0.09 g/cm^3 for SSP2+ and 0.28 g/cm^3 for SSPPTD+ and a low energy density (Table 8). A hydraulic press was used to compress the selected mixtures. As a result, cylindrical briquettes with a diameter of 25 mm, a height of 10–15 mm, and a bulk density of 0.9–1.6 g/cm^3 were obtained (Table 8).

Table 8. Bulk density of the mixtures/briquettes.

Mixture /Briquette	Bulk Density of the Mixtures, g/cm^3	Bulk Density of the Briquettes, g/cm^3	
		Pressure	
		100 MPa	150 MPa
SSPPTD+	0.28	0.9	0.84
SSD1+	0.24	0.91	0.81
SSP2+	0.09	1.59	1.61

SSD1+ and SSPPTD+ briquettes have a suitable degree of solidification and hardness. Transverse cracks that weakened compactness were noticed in briquettes higher than 15 mm (Figure 9). In both cases, smaller amounts of material should be applied to the die to obtain briquettes of sufficient height (10–15 mm) and better durability. The delamination in briquettes with a height greater than 15 mm may be due to the phenomenon of sample decompression after taking it out of the mold and the content of plastics fractions of bigger dimensions, which, after pressing, return to the previous size. According to the work of [43], many factors can affect the results of sample pressing, including the amount of material pressed, pressure, moisture content in the mixture, fineness of the material, binding agents, and many others. Therefore, a wide range of additional research is required for an accurate understanding of the briquette manufacturing process.

Figure 9. Briquettes of SSP2+, SSD1+, and SSPPTD+ (pressure 100–150 MPa).

The analysis of moisture loss as a function of time for selected mixtures clearly indicates the energy gain associated with drying of the valorized sludge (Figure 10). The

drying time to working value for the SSD1+ mixture was reduced by 50%, SSP2+ by 54%, and SSPPTD+ by 60% compared to the drying time of sludge alone.

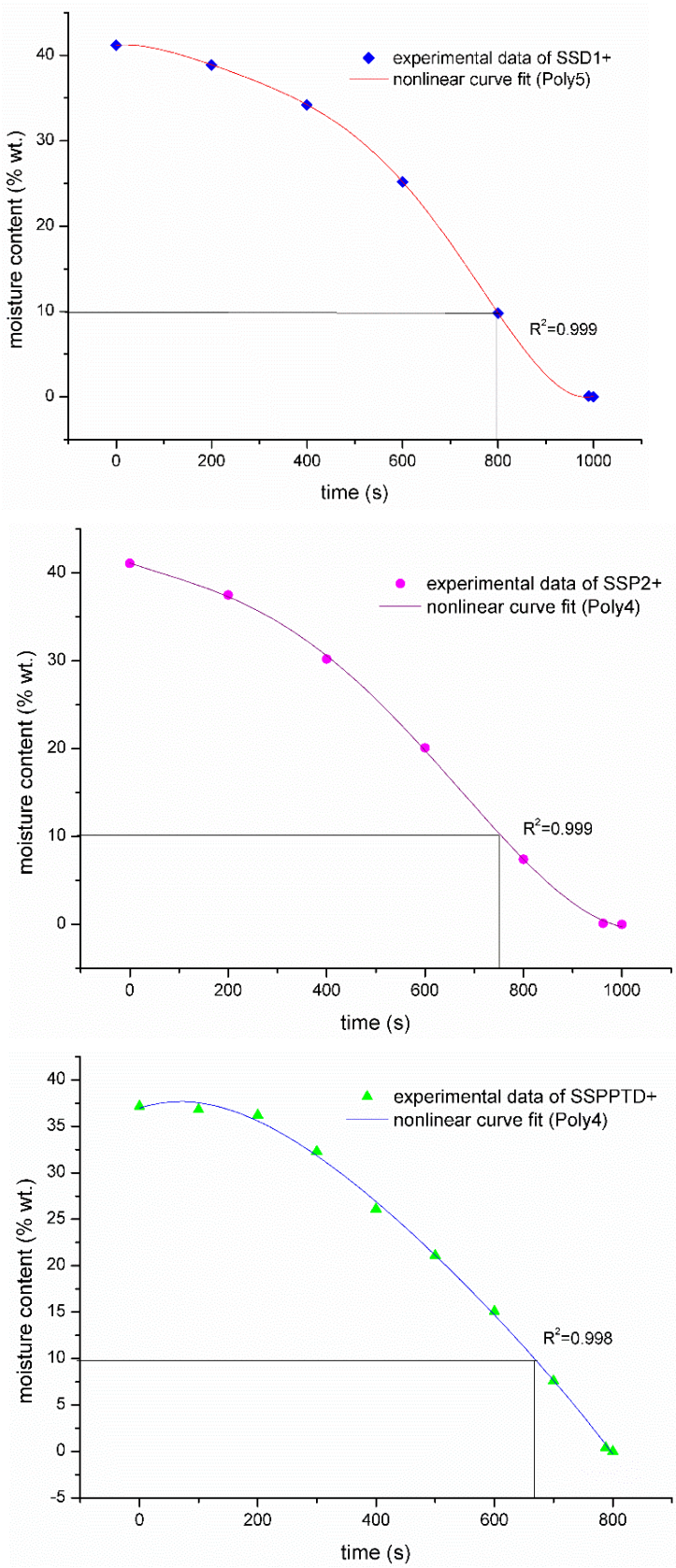


Figure 10. Moisture content as a function of time of SSD1+, SSP2+, and SSPPTD+.

According to design assumptions, sewage sludge in belt dryers should have a moisture content of approximately 60%. In order to reduce the moisture content from 80% to 60%, it is assumed to introduce 0.3 Mg of dried sludge per 1 Mg of wet sludge to avoid the phenomenon of sludge "sticking". Dry sludge is poorly wettable, which does not completely reduce this problem. The proposed valorization of digested sewage sludge before the drying process changes the structure of the sludge and significantly reduces its moisture content. It improves heat convection and facilitates moisture outflow. Using the low-moisture waste and higher calorific values for valorization shortens the time of sludge drying by 50–60% while reducing the energy consumption of the process by the respective value. According to the work of [44], the energy needed to produce pellets using sewage sludge and biomass (50 + 50%) was 50% lower than the energy needed to produce pellets from pure biomass. The phenomenon of sludge "sticking" is beneficial in the proposed solution by facilitating the formation of the final product in the form of briquettes and increasing their compactness and durability. Kubonova et al. [45] showed that sewage sludge is a very suitable binder for individual components of the alternative fuel, at the same time indicating that the moisture content of sewage sludge (about 72 wt.%) was an advantage for mixing with other types of waste.

The next stage of the research was to carry out elemental analysis of the mixtures, to determine the combustion heat, and to calculate the calorific value in the analytical state and in the working state for moisture content of 10%. Depending on the type of substrate and its percentage in the valorized sewage sludge mixtures, the results obtained varied (Table 9). The heat of combustion is directly proportional to the content of C and H and inversely proportional to the ash content. Sewage sludge valorized with wood dust (SSD1+, SSD2+, and SSD3+) had a calorific value ranging from 15.8 to 16.6 MJ/kg. Mixtures consisting of sludge and waste paper reached values ranging from 14.2 MJ/kg for SSP1+ to 15.2 MJ/kg for SSP3. The mixtures of sewage sludge valorized with waste plastic and wood dust have the highest calorific value, with 22.2 MJ/kg for SSPPTD+ and 23.9 MJ/kg for SSPET+. Chen et al. [46] showed that the fuel made from sewage sludge and wood dust in a proportion of 10:1, with a moisture content of 14.2–18.5%, is characterized by a calorific value of 21.8–23.4 MJ·kg^{-1}. The fuel obtained by the authors met all the requirements of the Taiwanese company Taipower. According to the work of [47], the calorific value of pellets consisting of sewage sludge and fir (CFSP) was 17.54 MJ/kg. These results are comparable to SSD1+, SSD2+, and SSD3+, respectively. Park et al. [48] showed that if 50% of waste plastics is included in the mixture, it is possible to achieve a calorific value of about 23 MJ/kg for the RDF. Valorization of sewage sludge in the proportions 1:1:1 (sewage sludge: waste plastics: wood dust) allowed to obtain a comparable calorific value.

Table 9. Elemental analysis, HHV and LHV of briquettes.

No	Symbol of Briquette	Element				Ash Content	HHV	LHV	LHV (Moisture 10%)
		C	H	S	N				
		%				%	MJ/kg	MJ/kg	MJ/kg
1	SSD	44.50	5.70	0.400	1.36	24.00	17.40	16.18	15.9
2	SSD1+	44.62	5.75	0.397	1.34	23.90	17.30	16.09	15.8
3	SSD2+	45.68	5.80	0.360	1.41	23.56	17.90	16.60	16.4
4	SSD3+	46.17	5.81	0.344	1.38	23.08	18.07	16.77	16.6
5	SSP1	39.85	5.87	0.397	1.31	26.30	15.95	14.63	14.4
6	SSP2	40.50	5.95	0.325	1.33	25.00	16.30	14.90	14.8
7	SSP1+	39.02	5.90	0.343	1.40	26.80	15.70	14.40	14.2
8	SSP2+	40.75	6.03	0.312	1.29	25.50	16.40	15.08	14.8
9	SSP3+	41.24	6.19	0.258	1.35	24.40	16.80	15.40	15.2
10	SSPPT	64.00	6.75	0.300	1.36	22.50	25.38	23.86	23.7
11	SSPPTD	59.65	6.79	0.266	1.37	21.00	24.00	22.38	22.3
12	SSPPT+	63.70	7.20	0.294	1.37	23.05	25.80	24.17	23.9
13	SSPPTD+	59.52	6.84	0.264	1.41	21.61	23.90	22.38	22.2

According to the requirements for alternative fuels specified in the PN-EN-15359:2012 standard [49], there is a division into fuel classes in terms of the net calorific value. Class 2 comprises fuels with a calorific value of ≥20 MJ/kg, including sewage sludge mixtures valorized with waste plastic (SSPPT+) or in combination with wood dust (SSPPTD+) with the calorific value of 23 MJ/kg. Class 3, according to PN-EN-15359:2012 [49], with a calorific value above 15 MJ/kg, includes sewage sludge mixtures valorized with wood dust (SSD, SSD1+, SSD2+, and SSD3+). The mean calorific value, in this case, is 16.2 MJ/kg. Class 4, with a calorific value above 10 MJ/kg, includes all sewage sludge mixtures valorized with waste paper, with a mean calorific value of 14.7 MJ/kg.

3.3. Approximation of Sewage Sludge Valorization

The values presented in Table 10 can be treated as a set of numerical data that can be written in general form as:

$$\{(u_1)_1, (u_2)_1, \ldots, (u_k)_1, z_1\}, \{(u_1)_2, (u_2)_2, \ldots, (u_k)_2, z_2\}, \ldots, \{(u_1)_n, (u_2)_n, \ldots, (u_k)_n, z_n\} \quad (8)$$

where $(u_l)_j$, $l = 1, \ldots, k$, $j = l, \ldots n$, are the shares of particular components in sample j (total number of sample is $n = 13$). Each sample is described by the set of components k (here $k = 5$), and the particular indexes denote: 1-sewage sludge (SS), 2-wood dust (D), 3-waste paper (P), 4-mixed waste plastics (PPT), and 5-polyvinyl alcohol and calcium oxide (+). Values of z_j, $j = 1, \ldots n$, denote the "calorific values" of the sample j and are determined experimentally.

Table 10. Set of numerical data and approximation of sewage sludge valorization.

No	SS	D	P	PPT	+	z	z_{approx}	$\lvert z_{approx}-z \rvert$	$(z_{approx}-z)^2$
	u_1	u_2	u_3	u_4	u_5				
1	0.5	0.5	0	0	0	15.7	15.61	0.09	0.0081
2	0.49	0.49	0	0	0.02	15.6	15.65	0.05	0.0025
3	0.41	0.57	0	0	0.02	16.1	16.12	0.02	0.0004
4	0.37	0.61	0	0	0.02	16.3	16.35	0.05	0.0025
5	0.63	0	0.37	0	0	14.2	14.02	0.18	0.0324
6	0.5	0	0.5	0	0	14.5	14.49	0.01	0.0001
7	0.62	0	0.36	0	0.02	13.9	14.09	0.19	0.0361
8	0.49	0	0.49	0	0.02	14.6	14.55	0.05	0.0025
9	0.38	0	0.6	0	0.02	14.9	14.95	0.05	0.0025
10	0.5	0	0	500	0	23.3	23.58	0.28	0.0784
11	0.333	0.333	0	0.333	0	21.9	21.9	0	0
12	0.49	0	0	0.49	20	23.7	23.46	0.24	0.0576
13	327	0.327	0	0.327	0.02	21.9	21.83	0.07	0.0049

On the basis of the given data in Table 10, the numerical values of p_l are equal to: $p_1 = 12.695874$, $p_2 = 18.527441$, $p_3 = 16.282293$, $p_4 = 34.465184$ and $p_5 = 17.626107$. The calculated values of p_l allow us to determine the calorific value for any share of particular components in the sample using the approximation Formula (1). Table 10 presents the calculated values z_{approx} on the basis of Equation (1) for the determined parameters p_l and the component shares (u_l) in each sample. The square error $(z_{approx}-z)^2$ was determined for each sample j.

4. Discussion

Waste with energetic potential should be used locally all over the world. This is supported by the limitation of the use of conventional energy sources and the limitation of landfilling. Guidelines for this can be found in the Directive of the European Parliament and of the Council 2018/850 from 30 May 2018 [50] amending Directive 1999/31/EC concerning the storage of waste [51].

According to the European Commission's report [52], the term refuse-derived fuel (RDF) refers to waste that has been processed to meet industry requirements, mainly those concerning high calorific value. RDF should include specific fractions of municipal waste, industrial and commercial waste, sewage sludge, industrial hazardous waste, and biomass. Municipal waste, including selectively collected fractions, can be used to produce alternative fuel for energy recovery in the cement kiln installations. It is possible to add waste from other waste groups (without hazardous waste) to achieve the parameters expected by the cement plant. Preferred parameters of alternative fuel are: moisture content < 20%, calorific value > 20 MJ/kg, sulfur content < 1%. Deviations from the required parameters can be agreed upon on a case-by-case basis, taking into account the specific design of the installation [53,54]. Restrictions on the chemical composition of the refuse-derived fuel depend on individual kiln installations. The content of trace components in the raw materials for clinker production in the basic fuel and in the refuse-derived fuel is taken into consideration. Furthermore, it is also important how and where the fuel is collected for the installation. The use of biomass waste for energy purposes makes it possible to meet environmental standards for emissions of CO_2, SO_x, NO_x, dust, dioxins, chlorine, mercury, and heavy metals. Biomass burning reduces the balance of CO_2 emissions because the amount of CO_2 previously collected from the environment is released into the atmosphere. The low nitrogen content of biomass waste reduces the emissions of NO_x compounds into the atmosphere compared to burning coal [55,56].

The diagram (Figure 11) shows a typical solution for a sewage treatment plant (a) and the feasibility of the solution presented in the article (b) that would consist in the use of a "bypass" between the centrifuge and, for example, a sludge belt dryer. The "bypass" would consist of a homogenizing mixer and a press. The supply of waste materials in the form of waste paper (P), wood dust (D), and waste plastics (PPT) would not generate costs as it would burden the supplier.

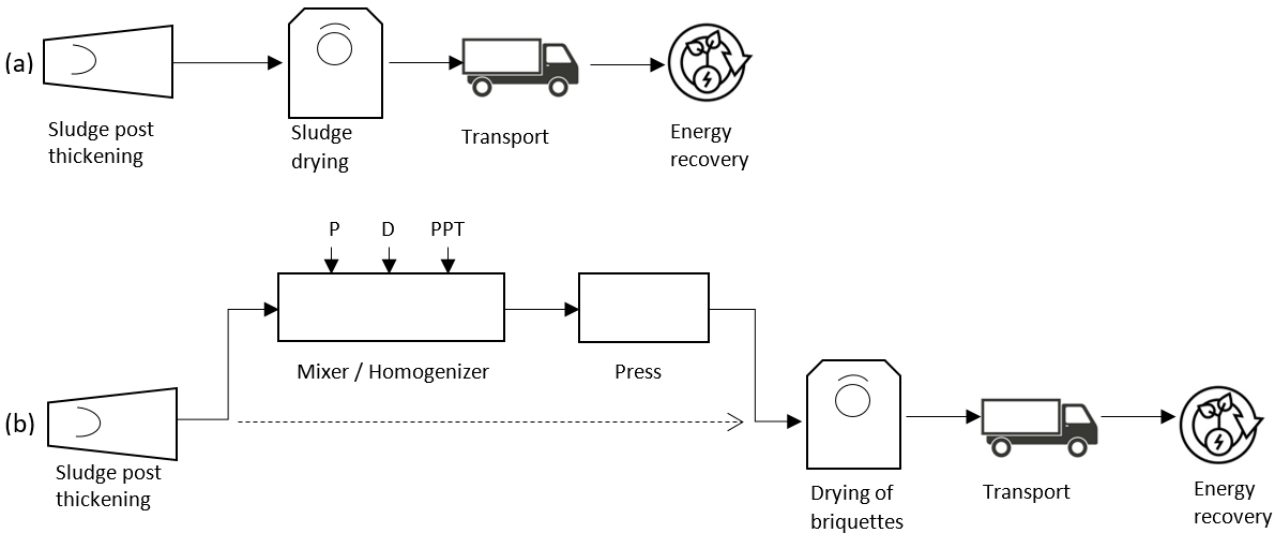


Figure 11. Scheme of (**a**) typical solution for sewage sludge treatment, (**b**) feasibility of sewage sludge valorization.

The difficulties arising from the mixing of waste are related to its variable composition and differences in physical and chemical properties. This requires constant laboratory control of the quality of refuse-derived fuels [57]. Examination of sewage sludge valorization was oriented at obtaining a high calorific value and reducing the carbon footprint related to wood dust and waste paper. Valorization with mixed waste plastics does not contribute to reducing the carbon footprint of the obtained product. However, this does not mean that there is no reduction in the carbon footprint of the obtained SSPPTD+ product, where the proportion of individual substrates is 1:1:1 (sewage sludge: waste plastics: wood dust). The consequences for atmospheric emissions when burning valorized dried

sewage sludge will be insignificant because, in the structure of heat from individual fuels used for clinker production, dry sewage sludge constitutes 0.17–3.1% in cement plants in Poland [58,59]. The PP and PET waste contained in the product does not contain chlorine, fluorine, mercury, and heavy metals. In the case of cement plants, flue gas emissions are continuously monitored, which guarantees compliance with the restrictive emission standards for individual compounds (NO_x, SO_x, TOC, CO, HCl, HF, dust). Many other parameters determining the furnace operation are automatically adjusted to the level of recorded emissions. This provides the ability to respond when elevated levels of hazardous compounds occur [60].

Digested and dried sewage sludge is a substitute for fuel used in cement plants. The low calorific value of the fuels (13–15 MJ/kg) limits their substitution in the cement industry to about 5–10% [42]. An increase in the calorific value of the valorized sewage sludge above 20 MJ/kg, at a low moisture content of 10% H_2O, makes it possible to substitute the fuel used in cement plants by up to 50%. In energy and environmental terms, it is an attractive fuel for the consumer. CO_2 emissions are limited for the cement industry. Sewage sludge represents biomass and is neutral in terms of CO_2 emissions [61].

The selected products obtained through sewage sludge valorization are characterized by a calorific value of 22–23 MJ/kg, which makes it possible to use them for co-combustion with coal in the energy industry. This requires additional testing to accept them for use in boiler equipment. Furthermore, attempts will be made to perform mono-combustion of the products at the wastewater treatment plant combined with energy recovery, phosphorus recovery from ash, and use of the mineral residue in the construction industry.

5. Conclusions

Based on the performed analyses, the following conclusions can be formulated:

1. The current degree of substitution of conventional fuels with alternative fuels in the cement industry has exceeded 40% on average in Poland. This has raised expectations for alternative fuels with a required calorific value of 20 MJ/kg;
2. Most biomass fuels have a calorific value of 16–18 MJ/kg. The proposed valorization of sewage sludge increases this value up to 23 MJ/kg;
3. The valorization of biomass waste with the waste with high calorific value ensures the possibility to carry out energy recovery in cement industry installations, in accordance with their technological requirements;
4. The mass fraction of biomass in the valorized sewage sludge ranges from 50% to 60%. This improves the balance of CO_2 emissions, which is limited in the cement industry;
5. The valorization of sewage sludge with low-moisture waste reduces the energy consumption of the drying process in sewage treatment plants by up to 50%;
6. The sludge adhesion to the drying belt observed in the drying process is a favorable parameter in the case of solidification of the product in the form of briquette or granulate. It ensures the durability and compactness of the product.

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