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The Use of Waste Biomass from the Wood Industry and Municipal Sources for Energy Production

Andrzej Greinert [1,*], Maria Mrówczyńska [2] and Wojciech Szefner [3]

[1] Institute of Environmental Engineering, University of Zielona Góra, 65-516 Zielona Góra, Poland
[2] Institute of Civil Engineering, University of Zielona Góra, 65-516 Zielona Góra, Poland; M.Mrowczynska@ib.uz.zgora.pl
[3] Lubuski Centre for Innovation and Agricultural Implementation Ltd., University of Zielona Gora, Co., Kalsk 122, 66-100 Sulechów, Poland; w.szefner@loiiwa.com.pl
* Correspondence: A.Greinert@iis.uz.zgora.pl

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Abstract: Biomass can be used for the production of energy from renewable sources. Because of social resistance to burning crop plants, mixtures and pellets made from or including waste materials are a good alternative. The mixtures analyzed, prepared from wood and municipal waste, were characterized for their calorific values, 7.4–18.2 MJ·kg^{-1}. A result, over 15 MJ·kg^{-1} was obtained for 47% of the quantities of mixtures being composed. It has been demonstrated that wood shavings and sewage sludge have a stabilizing effect on the durability of pellets. The emissions of acidic anhydrides into the atmosphere from the combustion of pellets from waste biomass were lower for NO, NO_2, NOx and H_2S than emissions from the combustion of willow pellets. Obtained emission results suggest the need to further optimize the combustion process parameters.

Keywords: energy from biomass; pellets; wood waste; municipal waste

1. Introduction

The production of energy by burning solid fuels as the main item in energy mixes is prevalent across many countries in the world, including the largest energy producers, such as the USA, China, India and most of the European Union (EU) countries. It seems that coal fuels will remain an important element of their economies for at least several dozen years [1]. The share of energy from renewable sources in final energy consumption in the EU-28 and in Poland in 2016 was 8.0% and 8.3%, respectively. In 2013–2016, there was an increase by 0.4% in the EU-28, but a decrease by 0.6% in Poland [2,3]. In 2016, the structure of primary energy production from renewable sources in the European Union included a share of 44.7% of solid biofuels and 4.7% of municipal waste in this stream but the results for Poland are different—70.7 and 0.9%, respectively. In 2016, in the EU, solid biomass had a 15.2% share in the structure of the consumption of household energy from individual energy carriers. A smaller index has been noted in Poland, 13.5% [3], and for the whole world, 10–14% [4]. The 27 EU member states have a high potential for waste biomass for energy applications, calculated at 8500 PJ·y^{-1} [5]. The use of biomass for energy production has a number of advantages, such as low costs and high availability, which lowers the costs of transport and reduces its environmental impact [4,6,7]. It is also important that biomass can be used both in the boilers of the power industry to generate heat and electricity as small individual heating installations [8]. The market for biomass pellets is growing systematically on a global scale. As a result, woody and herbaceous biomass will be more difficult to obtain [9]. Difficulties are also noted in the access to wood and agricultural residues in many places around the world, i.e., African countries [8].

Large amounts of waste with a significant potential for energy production are produced by the wood industry (logging and wood processing residues)—up to 27% of the wood mass. Up to 42% of this waste can be obtained for energy purposes [8]. Poland is a country with a relative high forest residues theoretical potential in the EU [5]. This waste contains 43–51% of carbon, and the heat generated by its combustion reaches 18.5–20 MJ·kg^{-1}, which makes it a valuable energy material [10,11]. An additional advantage is the low amount of ash produced during the combustion of the wood residues, ranging from 0.4 to 2.0%. The use of a mixture consisting of 80% of sewage sludge, 19% of wood dust and 1% of quicklime produced results that proved that a widespread use of this type of fuel was possible since the heat generated by its combustion was slightly over 13 MJ·kg^{-1}. Replacing wood dust with coal dust raised this value to 19 MJ·kg^{-1}. Attention is paid to the hygroscopy of this fuel and its susceptibility to crumbling under the influence of moisture [11]. Due to the high price of wood obtained from forests by the wood industry using typical methods, slash and waste material obtained by pruning trees and shrubs are used to produce pellets. Wood from short cultivation cycles of *Populus, Salix, Eucalyptus* and *Robinia* is also used [12]. This method of wood management is also used in agriculture in orchards [13,14]. Forest residues and straw are counted as the top two contributors of energy from the residual biomass in the EU—7000 PJ·y^{-1} [5]. Agriculture is the main source of fuel biomass in the world. In this context, apart from trees and shrubs, attention is paid to the cultivation of energy plants and the use of post-harvest waste for this purpose [6]. Among agricultural crops, the typical biomass used for energy production are cereals, miscanthus, mallow, rapeseed, sunflower, and Jerusalem artichoke, but also agricultural residues such as vine, shrub and fruit tree shoots, corn stalks, peanut and hickory shells [14–16]. According to Hamelin et al.'s elaboration, the straw theoretical potential in Poland is high compared with many other EU-27 countries [5]. Pellets from vine shoot biomass have a standard calorific value for a majority of biomass types—18 MJ·kg^{-1} [14]. Due to the large diversity of agricultural crops and residues, the possibility of their recovery for energy purposes varies from 19 to 75% of the total mass [8].

The third of the important biomass sources for modern energy production, after wood and agricultural products, is municipal waste. Solid municipal waste (residues from urban green areas, roadside vegetation, food, paper, textile) and sewage sludge are used for energy production, both as homogeneous fuels, as well as in mixtures with other biomass for co-combustion with coal. There is a lot of information about the difficulties in the management of municipal waste due to the significant differentiation of their properties [17]. Chen et al. [18] suggested using fuel in the form of granules from sewage sludge and wood dust in a proportion of 10:1, with a moisture content of 14.2–18.5%, in the form of granules with a diameter of 2 and 7 mm. The results (a calorific value of 21.8–23.4 MJ·kg^{-1}) were favorable and the fuel proved to meet the requirements of the Taiwanese company Taipower. Also, Jiang et al. [19] mentioned sewage sludge as an interesting material that could be a biomass binder in the production of pellets. According to these authors, the addition of sewage sludge reduces the energy needed to compress and extrude materials during the production of pellets, increases the density and hardness of pellets (reducing dust during transport and operation) and improves combustion parameters. The downside is an increase in the weight of combustion residues in comparison to pure wood and herbaceous biomass. Stabilized sewage sludge contains 40–70% of carbon in its dry matter, which means that these materials could be used for energy production [20,21]. Nevertheless, the process of preparing sewage sludge for combustion and co-combustion is so expensive that the rolling costs of this type of use are not very favorable—in Poland, 375–438 € for 1 Mg d.m., compared to 75–150 in agriculture and reclamation [20]. An additional problem is the amount of ash generated from this material, which is greater than in the case of most other fuels—an average of 36.4% for sewage sludge as against approx. 1% for wood, 6% for wheat straw and 19–22% for coal [22,23]. Therefore, the co-combustion of sewage sludge should be redefined to find an innovative method for the preparation of this material before its use for energy production. Apart from energy production, the new material has to give end users measurable financial benefits in the form of better furnace operating parameters. Yilmaz et al. [24] showed that the best results could be obtained by burning pellets with a size of 35 mm made from waste from plant oil production and sewage sludge. These authors noticed the high susceptibility of pellets to mechanical degradation under the influence of moisture and, for this reason, they recommended short-term storage under conditions that would counteract the moistening of the material. Jiang et al. [25] showed that better results could be obtained by burning pellets made from a mixture of sewage sludge and wood biomass than sewage sludge alone. As far as energy production is concerned, pellets are much more efficient than raw biomass. Increasing biomass density reduces transport costs and improves combustion parameters [26]. When pellets are formed, it is possible to control their composition, and when they are finally used, it is possible to automatically feed them to the furnace.

In the literature, there is little mention of the process of granulation/pelletization of energy materials with the use of municipal waste. Relatively few tests of this type have been conducted on sewage sludge for only a couple of years. Li et al. [27] presented optimum parameters for the production of pellets from biomass and sewage sludge (50 + 50%): pressure 55 MPa, temperature 90 °C and moisture in the material 10–15%. The energy needed to produce pellets using sewage sludge was 50% lower than the energy needed to produce pellets from pure biomass. Similar moisture parameters of material intended for pelletization were reported by Kliopova and Makariski [28]. Kijo-Kleczkowska et al. [23] obtained pellets with densities of (kg/m^3): 1089.2 (hard coal), 859.9 (sewage sludge), 802.6 (lignite), 363.1 (*Salix viminalis*), 898.1 (50% sewage sludge + 50% hard coal), 803.5 (50% sewage sludge + 50% brown coal), and 515.9 (50% sludge + 50% *Salix viminalis*). There were a number of changes in the process of combustion of particular solid biofuels after the addition of sewage sludge. Jiang et al. [19] analyzed the possibilities of pelleting energy materials using sewage sludge and noticed an increase in the density of pellets obtained while increasing pressure to 28, 41, 55, 69 and 83 MPa. A further increase in pressure to 110 MPa no longer caused any significant differences. The increase in density and hardness of pellets was also the resultant of the share of sewage sludge (from 20 to 80%). The temperature during pelletization should not exceed 110 °C, and the content of moisture in the input material should not exceed 15%. Higher temperatures and humidity reduce the density of pellets. If granulates/pellets based on limed sludge and other selected solid waste are to be used for co-combustion with biomass in heating furnaces, it is necessary to prepare a production technology that will make them easy to produce repeatedly and make them profitable to producers, easy to transport, easy to use precisely, effective during biomass combustion and safe. They should also generate ash that is easy to remove from furnaces and environmentally safe. García-Maraver et al. [29] noticed that the process of the preparation of heating pellets and their physical, physicochemical and chemical properties had a significant impact on the combustion process and emission parameters. Lehtikangas [30] stated that it was necessary to use physically stable materials in the combustion process due to the possibility of disturbing the operation of automatic fuel feeders and advanced systems of automatic furnace control by dust. Moreover, this author noted that the temperature in the furnace could increase significantly (due to the combustion of dusts), which would lead to the melting of combustion residues. According to Sarenbo and Claesson [31], the production of granulate has to be effective, the granulate binder must not adversely affect the properties of the whole aggregate, and the final chemical composition and stability of the aggregate has to be consistent with the recommendations for a particular type of use for the material. Thus, the problem arises of developing a technology that will make it possible to produce granulates/pellets with the desired characteristics and properties. During previous research projects dealing with the granulation/pelletization of materials, the problem of the durability of products and their homogeneity was noted.

Emissions from the combustion of carbonaceous materials may be an obstacle to a wider use of biomass for energy production [7]. In this respect, attention is paid to the emission of CO_2 to the atmosphere as one of the main gases affecting the greenhouse effect. Nevertheless, in comparison to the combustion of solid fossil fuels, the combustion of biomass leads to a reduction in CO_2 emissions to the atmosphere when co-combustion technology is used [6,16]. As far as the so called carbon footprint is concerned, biomass is neutral to carbon circulation in the environment [10]. Biomass combustion also results in the emission of gases other than CO_2 (including NOx, CO, SO_2, hydrocarbons) as well as dust polluting the atmosphere, especially when combustion does not take place in optimum conditions. It is often mentioned in the literature that the emission of these gases to the atmosphere could be reduced by mixing fuel with lime and lime and dolomite dust, which in terms of chemical properties are mainly calcium compounds: $CaCO_3$, CaO, $Ca(OH)_2$ [7,31–33].

The study was carried out in a region with the largest forest cover in Poland—49.3% of the total area and 51.7% of the land area of the region, compared to 30.5% for the whole country. The wood industry plays one of the key roles in its economy—wood acquisition amounts to 3.6 $kdam^3$ per year [34]. Data on municipal waste management show that the amount of municipal waste that is combusted is still small, amounting to 19.4% of the total waste stream in the Lubusz region, compared to 24.4% in Poland [35]. Counting the current energy production from biomass in Poland in relation to the theoretical potential of this source (20–30% of the final energy consumption [5]), there is still a large reserve for activities intensifying this process. The use of waste from the wood industry as a fuel material allows to reduce the amount of this waste and reduce the energy demand from conventional sources. This approach also reduces the use of natural resources while meeting the energy needs of the population, so socio-environmental systems would be sustainable [36]. In order to further develop the thermal management of waste biomass, it is necessary to solve problems related to the emission of pollutants into the atmosphere. The aim of this study was to show the possibility of using waste generated in this region in large quantities as a renewable energy source. In many wastewater treatment plants, sewage sludge is still hygienized with lime. Materials prepared in this way are usually used as a soil improver. Therefore, the question was asked whether it could also be used as an improver in the biomass combustion process. For this purpose, it was considered whether it would be possible to use waste from the wood industry and limed municipal sewage sludge to produce solid fuel in the form of pellets with good thermal properties and at the same time ecologically safe. It was hypothesized that the addition of limed sewage sludge to fuel made from biomass would reduce the emission of such gases as acidic anhydrides.

2. Materials and Methods

A number of tests were carried out to find out whether it would be possible to produce durable pellets with good thermal properties from waste biomass. They included:

- Evaluation of input waste materials available in the region in large quantities;
- Preparation of mixtures of input materials and checking their thermal properties;
- Preparation of pellets from selected materials with the best properties in two groups—with lime and without lime;
- Testing pellet durability under high humidity conditions;
- Burning pellets under controlled conditions;
- The input materials for the tests were: straw, wood shavings, wood dust and sewage sludge hygienized with lime;
- Straw (S)—raw material obtained from a producer of straw pellets, homogeneous, crushed to a fraction of approx. 2 cm in length and packed in 10-kg bags; 100 kg of material was obtained for the needs of the experiments;
- Wood shavings (WS)—raw material obtained from a carpenter's workshop, material from debarked wood, non-homogeneous fraction from 1.5 to 3.5 cm; the material was not additionally sieved for the tests; 100 kg of material was obtained for the needs of the experiments;
- Wood dust (WD)—raw material obtained from a carpenter's workshop, material from debarked wood, homogeneous fraction, powder; the material was not additionally sieved for the tests; 100 kg of material was obtained for the needs of the experiments;
- Sewage sludge (SS)—from the Krosno Water Utility Company Ltd. (Krośnieńskie Przedsiębiorstwo Wodociągowo-Komunalne Sp. z o.o.); municipal sludge treated with lime in an innovative

installation for simultaneous hygienization and granulation of sewage sludge, using lime (CaO) in a sediment to a lime ratio of 1:0.9 by weight; the material was pre-screened through a 3-mm mesh sieve; the subscreen fraction was taken for testing; 100 kg of the material was obtained for the needs of the experiments.

For transport to the research place, the materials were packed in plastic bags, which were opened on the spot to avoid the phenomenon of organic material thermal degradation.

Each material was pre-homogenized to obtain a homogeneous mass with average properties. The homogenization process was carried out by hand, using a table for mixing substrates onto which a particular material was poured from the transport packaging. Each material was mixed for about 10 min. At the end of the homogenization process, 102 samples of materials (34 variants, 3 repetitions, 100 g each sample) were taken for laboratory analysis. In each case, the method of average pooled samples was used. The mixed samples consisted of 30 individual samples taken from the entire volume of the material.

The materials were analyzed in laboratory conditions in terms of:

- bulk density—by weight in 5 repetitions, from which the mean and standard deviations were calculated;
- the calorific value—using a calorimetric bomb Parr 6100, acc. to norm PN-C-04375-2:2013-07, in 3 repetitions, from which the mean and standard deviations were calculated;
- the total carbon content—using the Pregla–Dumas method, the samples were combusted in a pure oxygen environment and the resulting exhaust gases were automatically measured using a CHNS/O 2400 Series II PerkinElmer elemental analyzer. The measurements were conducted for weights of 1.5–2.5 mg in three repetitions, from which the mean and standard deviations were calculated;
- the content of heavy metals (Cd, Cr, Cu, Ni, Pb and Zn) was measured using the ICP-OES method and a Perkin Elmer ICP-OES Optima 8000 spectrometer, after wet mineralization in concentrated nitric acid in a Perkin Elmer Titan microwave mineralizer, in three repetitions from which the mean and standard deviations were calculated;
- the content of K, Na, Ca, Mg and Fe by ICP-OES was measured using a Perkin Elmer ICP-OES Optima 8000 spectrometer, after wet mineralization in concentrated nitric acid in a Perkin Elmer Titan microwave mineralizer, in three repetitions from which the mean and standard deviations were calculated;
- pH—potentiometrically in a mixture of solid material (air dry) and water in a proportion of 1:5 using a pH-meter InoLab, with a WTW SenTix 41 glass electrode.

In order to obtain a homogeneous material, the samples were homogenized by grinding.

In laboratory conditions, mixtures of input materials were prepared and further components were weighed as shown in Table 1. Each mixture was ground to obtain completely equal properties before further analysis.

Table 1. Composition of the mixtures of materials.

Mixture Number	Composition of Components	Proportion of Components
M1	WS + WD	1:1
M2	WS + S	1:1
M3	WS + SS	1:1
M4	WD + S	1:1
M5	WD + SS	1:1
M6	S + SS	1:1

Table 1. *Cont.*

Mixture Number	Composition of Components	Proportion of Components
M7	WS + WD + S	1:1:1
M8	WS + WD	4:1
M9	WS + S	4:1
M10	WS + SS	4:1
M11	WD + SS	4:1
M12	S + SS	4:1
M13	WS + SS	9:1
M14	WD + SS	9:1
M15	S + SS	9:1
M16	WS + WD + SS	7:2:1
M17	WS + S + SS	7:2:1
M18	WS + WD + SS	3:1:1
M19	WS + S + SS	3:1:1
M20	WS + WD + SS	6:1:3
M21	WS + S + SS	6:1:3
M22	WS + SS	7:3
M23	WD + SS	7:3
M24	S + SS	7:3
M25	WS + WD + S + SS	3:3:3:1
M26	WS + WD + S + SS	1:1:1:2
M27	WS + WD + S + SS	1:1:1:1
M28	WS + WD + S + SS	3:3:3:11
M29	WS + WD + S + SS	1:1:1:7
M30	WS + WD + SS	3:3:4

Note: S—straw, WS—wood shavings, WD—wood dust, SS—sewage sludge.

Each mixture was analyzed in laboratory conditions in terms of:

- the calorific value—calorimetrically in three repetitions, from which the mean and standard deviations were calculated;
- pH—potentiometrically in a mixture of solid material (air dry) and water in a proportion of 1:5 using a pH-meter InoLab, with a WTW SenTix 41 glass electrode;
- electrical conductivity (EC)—conductometrically in a mixture of air-dry solid material and water in a proportion of 1:5; using a Eutech Instruments Cyberscan PC300 and Elmetron CPC-411 devices with an EC-60 conductivity sensor;
- the subtotal content of selected components—after the hot dissolution of substrate samples (in a Perkin Elmer MPS microwave oven) in a mixture of hydrochloric and nitric acid (aqua regia), using the ICP-OES method (Perkin Elmer Optima 8000)—ISO 11466 (1995);
- the total carbon content—using the Pregla–Dumas method, the samples were combusted in a pure oxygen environment, and the resulting exhaust gases were automatically measured using a CHNS/O 2400 Series II PerkinElmer elemental analyzer. The measurements were conducted for weights of 1.5–2.5 mg in three repetitions, from which the mean and standard deviations were calculated.

Based on the results of these analyses, mixtures expected to bring the best results in terms of energy production were selected. A total of 10 kg of each selected mixture were prepared for pelleting. A pelletizer, ZLSP200, 7.5 kW made by Eko-Pal, with a capacity of approx. 80–100 kg h^{-1} was used for pelleting. The input materials were mixed in the right proportions and brought to a humidity of 12–13%. After wetting, the mixtures used for pelletization were rested for 24 h. A matrix with a diameter of 6 mm was used in the process of pelletization. The matrix was not lubricated with any substances. During this process, the rotation speed of the pelletizer was not regulated, and only the pressure of the roller on the matrix was corrected for better performance. Each of the mixtures intended for pelletization was passed through the device until pellets of the right quality had been obtained—in some cases, the process was repeated three times. After the pellets were obtained, the output material was rested for 24 h before packing. After each of the individual mixtures was pelletized, oat husks were passed through the pelletizer to clean the sieve before working with the next mixture. Each time, the first batch of pellets obtained from a new mixture was also discarded in order to get rid of the remnants of the oat husks in subsequent completed mixtures.

The pellets were combusted in fully controlled conditions to obtain information about the combustion process and exhaust emissions. The pellets were combusted in a prototype FORST boiler equipped with two burners: 24 and 48 kW (modified Forster Heizkessel, PE40 boiler), adapted for burning biomass, with an automatic pellet feeding and ash removal system. Combustion of individual pellets was carried out after preheating the furnace to its optimal temperature, using a standard willow tree pellet. Each of the test pellets was fed to the boiler for 4 h. The main combustion parameters: incineration temperature 700–800 °C, air flow 20 m^3 h^{-1}, mass fuel consumed 1,5 $kg{\cdot}h^{-1}$, exhaust gas temperature 141–162 °C, exhaust gas mass flow 30 $g{\cdot}s^{-1}$, O_2 in exhaust gas 11–14%, max. operating temperature 90 °C, max. operating pressure 2.5 bar, pellet calorific value 17.73 $MJ{\cdot}kg^{-1}$, pellet residual moisture 8–9%, and ash production 3.84% of the pellet mass. The biomass boiler was included into the heat production and distribution system at the Laboratory of Thermal Technologies in the Renewable Energy Center (REC). The laboratory research system is equipped with an advanced measuring system based on measuring devices made by E&H. The exhaust duct of the boiler is equipped with a measuring connection for chemical analysis of exhaust gases. Measurement data are registered by the building management system, Building Management System (BMS), using the Wonderware System Platform. Exhaust gas was measured continuously using a TESTO 350 Xl exhaust gas analyzer. Emission measurements were conducted after the combustion conditions were stabilized, i.e., in the so called high-temperature combustion phase [37].

The following analyses of the pellets were performed in laboratory conditions:

- static and dynamic tests of moisture absorption by the pellets;
- test of the mechanical strength of the pellets;
- pH and EC analyses of water extracts after 48 h of incubation.

The static test of moisture absorption was carried out in 250-ml glass flasks. An amount of 10 g of pellets were poured into a flask and 90 cm^3 of distilled water were added. After 48 h of incubation at room temperature, the samples were subjected to gravity dehydration on sterile gauze for 10 min. After that, a visual evaluation of the disintegration was carried out, the pellets were weighed and the leachate was collected to the volumetric flasks, then the mechanical strength of the pellets was examined.

The dynamic moisture absorption test was carried out in 250-cm^3 plastic bottles. An amount of 10 g of pellets were poured into the bottles and 90 cm^3 of distilled water was added. The samples were shaken on a mechanical stirrer at 60 rpm for 1 h and they were left for 24 h at room temperature. After 24 h, the samples were again subjected to mechanical shaking at 60 rpm for 1 h. The pellets were then subjected to gravity dehydration on sterile gauze for 10 min. Decomposition was assessed visually, the pellets were weighed, and the amount of leachate was measured using the method of quantitative gathering to the volumetric flasks. Then, the mechanical strength of the pellets was examined.

Due to the disintegration of some of the pellets during the static and dynamic tests, mechanical strength was tested only in the samples that did not disintegrate. The study consisted in dropping each pellet from a height of 1.5 m onto a concrete surface and a visual assessment of disintegration.

The pH and electrical conductivity test was carried out in water solutions obtained by gravitational drainage of the pellets, pH was measured potentiometrically (using a WTW Inolab ph level 1 pH meter, with a WTW SenTix 41 glass electrode) in the supernatant of a 1:2.5 dry solid material: water suspension and EC was measured conductometrically (using a Cyberscan PC300 Series conductor) in the water-saturated paste. In the samples that completely disintegrated, pH and electrical conductivity were measured in the suspension and in the leachate obtained by mechanical filtration of the suspension.

3. Results and Discussion

3.1. Initial Observations

Although the materials used in this study consisted of waste generated on a large scale by industrial and municipal plants, they were morphologically balanced (Figure 1). While mixing the input materials, it was observed that large amounts of dust appeared during the process of mixing wood dust and limed sewage sludge with other materials. This will certainly be a problem both during the transport of these materials to the sites where mixtures and pellets will be prepared, as well as during the preparation of the products themselves. Nevertheless, the use of materials with a diversified structure promised well for the formation of pellets. By using particles of varying equivalent diameter, fiber length and shape, a compact mass of the mixture can be obtained. As a result, the pellets should have a higher bulk density and mechanical durability.

Figure 1. Input materials used in the study—wood shavings, wood dust, straw and limed sewage sludge.

3.2. Properties of the Input Materials

For subsequent input materials, the following bulk density values were obtained (mean ± standard deviation): WS—110 ± 5.4 kg·m^{-3}, WD—172 ± 5.0 kg·m^{-3}, S—85 ± 2.2 kg·m^{-3}, SS—845 ± 4.7 kg·m^{-3}.

This is important information because of the need to transport the materials to the site where they will be utilized. Since the materials will eventually be combusted, it is essential that with the relatively low bulk density of straw and wood shavings, the limiting criterion for transport will be the volume of material that can safely be loaded onto a transport vehicle—without the risk of uncontrolled scattering.

Although wood dust has the highest bulk density among these materials, it will also be problematic in transport because it generates large amounts of dust.

All biomass materials used in this study had a similar carbon content—from 48 to 53% of dry mass. The content of dry matter in them was also similar—within 90–92%. Sewage sludge hygienized with lime was a significantly different material; its carbon content was approx. 14% with 76% of dry matter. The pH analysis showed that the pH of straw was slightly alkaline, the pH of sewage sludge hygienized with lime was strongly alkaline, and the pH of the other materials—wood shavings and wood dust—was acidic (Table 2). The potassium content was clearly higher in the straw than in the other analyzed components. Straw was also characterized by a higher content of calcium than wood shavings and wood dust. Of course, the sewage sludge hygienized with lime has outperformed the remaining materials in this respect many times. Sewage sludge involves considerably higher contents of Fe, Cr, Cu, Ni, and Zn than other materials (Table 2).

Table 2. Selected physical and physic-chemical properties of the input materials.

Material	**C**	**Dry Mass**	**pH-H$_2$O**	**K**	**Ca**	**Mg**	**Na**	**Fe**	**Cd**	**Cr**	**Cu**	**Ni**	**Pb**	**Zn**
	(%)			**mg·kg^{-1}**										
WS	49.1	92.5	5.1	287	364	101	13	nd	nd	nd	nd	nd	0.8	4.0
WD	52.8	92.0	5.5	234	298	82	11	nd	nd	nd	nd	nd	0.7	3.3
S	48.0	89.8	8.0	2180	1109	120	5	16	nd	nd	nd	nd	nd	3.0
SS	13.9	76.0	12.4	307	75,700	348	48	433	nd	1.5	14	0.7	0.9	44.7

Similar results were presented by Houshfar et al. [10]. They indicated that the average content of carbon was 51.4% for wood pellets, 53.4% for wood waste and 49.5% for straw. A significantly higher content of C in sewage sludge was reported in the literature—28.4% [37], 48.9% [10], 53–60% [21]. However, in contrast to this study, that sewage sludge was not limed. In these analyses, we also obtained a dry mass of wood material and straw similar to that presented in the analyses of the cited authors—90.4–93.5% and 88.3%, respectively [6]. However, the dry mass of sewage sludge was smaller than presented in the literature. Chen et al. [38] indicated a content of 91.5% of dry matter for sun-dried sediments, but this is only 16–19% of the mass of raw sewage sludge as determined by Pulka et al. [21].

For subsequent input materials, the following calorific values were obtained (mean ± standard deviation):

- WS—16883 ± 755 kJ·kg^{-1} (4029 ± 180 kcal·kg^{-1})
- WD—14550 ± 1027 kJ·kg^{-1} (3473 ± 245 kcal·kg^{-1})
- S—18549 ± 753 kJ·kg^{-1} (4427 ± 180 kcal·kg^{-1})
- SS—no data (the material did not burn)

The analysis of the calorific value of the input materials showed the highest value for straw (by 11.3% higher than the mean for the materials analyzed), lower for wood shavings (1.3% higher than the mean for the materials analyzed), whereas for wood dust it was lower by 12.7% than the mean for the materials analyzed. The calorific value of the materials indicated that the most promising ones at this stage appeared to be straw and wood shavings. Due to the high content of minerals in the limed sewage sludge, it turned out that this material could be problematic as a fuel additive. The results for wood biomass and straw are typical as compared to those described widely in the literature, where calorific values within 16.5–20.5 MJ kg^{-1} [33,39,40] are most frequently recorded. The calorific value of sewage sludge is lower, amounting to 11.37 MJ·kg^{-1} [38], but always for non-limed sewage sludge.

3.3. Properties of Fuel Mixtures

It was noted that the addition of sewage sludge hygienized with lime had a significant impact on the pH of materials, the content of dry matter and content of total carbon (TC). The content of dry matter and total carbon are important properties in terms of the combustion characteristics of solid fuel, and the low pH may additionally affect the resulting emissions. Since different input materials were used in different proportions for the preparation of subsequent mixtures, significant differences were noted in the content of carbon in the mixtures, what was expected (Table 3).

Table 3. Properties of the mixtures of materials.

Material	**TC**	**Dry Mass**	**pH**	**K**	**Ca**	**Mg**	**Na**	**Fe**	**Cd**	**Cr**	**Cu**	**Ni**	**Pb**	**Zn**
	%			**mg·kg^{-1}**										
M1	50.9	92.2	5.4	521	662	183	24	n/a	n/a	n/a	n/a	n/a	1.49	7.33
M2	48.1	91.3	5.7	2094	1490	170	10	8	n/a	0.21	n/a	n/a	0.56	6.50
M3	28.1	87.2	12.3	598	74,571	396	55	430	n/a	1.36	12.56	0.56	1.55	44.57
M4	51.4	91.9	9.7	2788	1390	252	23	24	n/a	n/a	n/a	n/a	0.22	7.09
M5	30.3	86.3	11.4	537	77,432	482	65	436	0.02	1.58	14.54	0.76	1.62	52.07
M6	28.4	86.5	12.3	3159	53,465	428	43	352	n/a	0.65	8.27	0.14	0.79	33.23
M7	51.1	92.6	6.4	1460	1068	216	13	8	0.00	0.17	n/a	n/a	0.82	6.35
M8	51.0	93.4	5.1	536	692	139	17	n/a	n/a	0.02	n/a	n/a	0.43	7.57
M9	49.0	92.2	5.8	1481	2075	162	9	14	n/a	n/a	n/a	n/a	n/a	5.40
M10	42.9	91.3	12.2	674	48,413	314	40	295	n/a	0.60	3.28	n/a	1.46	22.68
M11	45.1	91.0	10.6	616	33,886	367	49	255	n/a	n/a	1.14	n/a	0.29	20.71
M12	37.2	89.6	10.9	3423	30,235	375	27	219	n/a	0.32	n/a	n/a	0.37	19.09
M13	46.8	91.9	12.0	572	13,453	159	16	107	n/a	n/a	n/a	n/a	0.32	11.27
M14	48.3	91.9	10.6	487	14,831	288	36	141	0.02	1.11	n/a	0.02	6.31	13.64
M15	44.4	90.3	11.9	3243	13,033	230	15	97	n/a	1.61	n/a	0.28	n/a	11.23
M16	46.2	91.8	11.7	587	16,868	177	20	139	0.02	0.48	n/a	0.31	1.31	13.20
M17	45.6	91.4	11.8	888	10,835	142	13	61	n/a	n/a	n/a	n/a	0.98	9.12
M18	42.4	91.2	12.2	526	28,130	256	30	223	n/a	n/a	0.21	n/a	1.06	21.01
M19	41.7	92.8	12.2	1047	32,961	264	27	280	n/a	0.40	2.40	0.22	0.91	19.96
M20	37.6	90.7	12.3	551	43,583	287	34	333	0.01	0.44	1.48	n/a	1.34	25.55
M21	37.0	89.9	12.3	866	50,099	359	39	418	n/a	0.70	7.84	0.30	1.30	29.62
M22	38.2	90.7	12.3	551	19,318	157	19	86	n/a	n/a	n/a	n/a	0.21	10.58
M23	40.3	90.6	12.0	598	74,572	396	55	430	n/a	0.42	3.87	n/a	0.35	24.09
M24	37.5	88.0	11.7	3929	19,347	292	20	142	n/a	0.04	n/a	n/a	n/a	11.91
M25	46.2	91.4	12.0	1806	12,046	220	21	96	n/a	0.09	n/a	n/a	0.16	10.67
M26	35.5	88.7	12.3	1323	52,593	354	44	377	n/a	0.33	4.43	0.07	0.30	26.40
M27	40.5	90.6	12.3	1525	34,102	310	33	259	n/a	0.18	1.50	n/a	0.52	17.07
M28	30.2	87.4	12.3	835	79,491	464	58	634	0.00	1.88	12.91	0.45	1.14	42.96
M29	23.3	86.0	12.3	842	10,3626	491	65	720	n/a	2.21	24.51	0.88	1.34	50.38
M30	35.2	89.4	12.3	463	62,336	364	45	431	0.01	1.29	8.36	0.55	1.80	28.70

In order to use waste from the wood industry as well as agricultural and municipal waste for energy production, one of the basic research paths to take is to determine the chemical composition of these materials. In this way, it is possible to determine whether this waste contains an excessive number of components that could be dangerous to the environment. During combustion, some of them will be released from the boiler as gases, some as dust and the remaining part will be present in the ash. The presence of certain components, such as sodium, potassium, calcium, magnesium and iron, may be undesirable because they leave residue on the grate and other elements of the boiler, causing technical problems. The high content of Ca, Mg, Na and Fe resulted from the addition of sewage sludge hygienized with lime to wood as well as agricultural and organic materials (mixtures: M3, M5, M23, M28 and M29). The high content of potassium resulted from the composition of material solely based on straw or with the presence of straw in the mixtures. As far as the chemical composition of waste materials is concerned, much attention is usually paid to heavy metals. They are not transformed by combustion, so they remain unchanged in the dust and ash after the combustion process. At the same time, when organic matter burns, its input mass decreases since some of it is transformed into gaseous products and it is deprived of water, the content of heavy metals is concentrated in combustion residues and fly ashes. For this reason, the content of heavy metals in solid fuels should be low. The content of Cr was in the range of 1.11–2.21 mg·kg^{-1} in materials M3 (WS + SS; 1:1), M5 (WD + SS; 1:1), M14 (WD + SS; 9:1), M15 (S + SS; 9:1), M28 (WS + WD + S + SS; 3:3:3:11), M29 (WS + WD + S + SS; 1:1:1:7) and M30 (WS + WD + SS; 3:3:4). In all cases, the mixtures included sewage sludge. There was no significant Cu, Ni and Pb content in all mixtures—max. 24.51 mg Cu kg^{-1} in material M29, 0.88 mg Ni kg^{-1} in material M29 and 1.80 mg Pb kg^{-1} in material M30. As far as the content of Zn is concerned, a relatively higher content was noted in mixtures M3, M5, M28 and M29, where it was in the range of 42.96–52.07 mg kg^{-1} (Table 3).

The majority of wood and agricultural waste does not contain large amounts of heavy metals. However, there are problems with their content in municipal waste. The data in Table 2; Table 3 clearly indicate the sewage sludge as a potential source of heavy metals in biomass mixtures. The content of some heavy metals (Cr, Ni) may also result from the degradation of the hardened steel elements of the screw biomass feeder, the boiler itself or the degradation of the collecting probes [17].

Since the content of carbon in raw wood and wood waste was similar, as expected, mixing these materials with each other did not cause any significant differences. This property was at similar levels to those described by other authors [10,14,16,32].

The analysis of the calorific value of the mixtures showed significant differences between particular materials (Table 4). Ten highest calorific values were obtained for mixtures (in decreasing order): M1; M2; M9; M8; M4; M7; M17; M10; M19; and M13. The weakest of these mixtures reached a calorific value lower by 11.8% than the best mixture. In the case of some of the mixtures, relatively higher values of the standard deviation (5–9%) were obtained, which indicates that the materials did not burn completely despite their homogenization: M5 (WD + SS; 1:1), M7 (WS + WD + S; 1:1:1), M11 (WD + SS; 4:1), M15 (S + SS; 9:1), M16 (WS + WD + SS; 7:2:1), M24 (S + SS; 7:3) and M27 (WS + WD + S + SS; 1:1:1:1). Most of these mixtures contained sludge in their composition, which may mean that its presence interferes with the combustion process.

Table 4. Calorific value of the mixtures of materials (value ± SD).

Mixture No.	Calorific Value (kJ·kg^{-1})
M1	18,219 ± 244
M2	17,755 ± 658
M3	10,755 ± 322
M4	17,115 ± 153
M5	13,110 ± 1134
M6	12,004 ± 469
M7	16,843 ± 916
M8	17,615 ± 633
M9	17,688 ± 90
M10	16,117 ± 278
M11	13,815 ± 2763
M12	14,330 ± 369
M13	16,061 ± 407
M14	15,660 ± 154
M15	14,686 ± 971
M16	15,692 ± 864
M17	16,530 ± 280
M18	15,325 ± 129
M19	16,098 ± 279
M20	13,612 ± 631
M21	14,501 ± 407
M22	13,892 ± 468
M23	14,950 ± 588
M24	13,847 ± 1289
M25	15,810 ± 315
M26	11,295 ± 659
M27	12,914 ± 1116
M28	9527 ± 96
M29	7408 ± 160
M30	11,366 ± 314

Sewage sludge hygienized with lime reduces the calorific value of mixtures. This is expected both due to its lower calorific value in relation to other biomass [38] and a high proportion of mineral compounds. The results were in the range of 7–18 MJ kg^{-1}, i.e., within a typical range for different waste materials in developed countries (8.4–17 MJ kg^{-1}) and they were better than the results obtained in China (3–6.7 MJ kg^{-1})—Zhang et al. [39]. The correlation between the calorific value of the mixtures of materials and the TC content (Figure 2) and dry mass (Figure 3) was also analyzed. The calculation of correlation coefficients makes it possible to determine the linear relation between the data and at the same time to eliminate irrelevant information from the data sets [41]. The relations between the calorific value and the TC content (correlation r = 0.91) and the calorific value and dry mass (r = 0.86) were characterized by a high positive correlation. These relations, widely described in the literature [42], were expected. Ngangyo-Heya et al. [42] performed correlation analyzes for components of woody biomass without leaves, indicating the correlation of the calorific value with some of its properties. The highest positive correlation between the biomass calorific value, pH and lignin content have been noted.

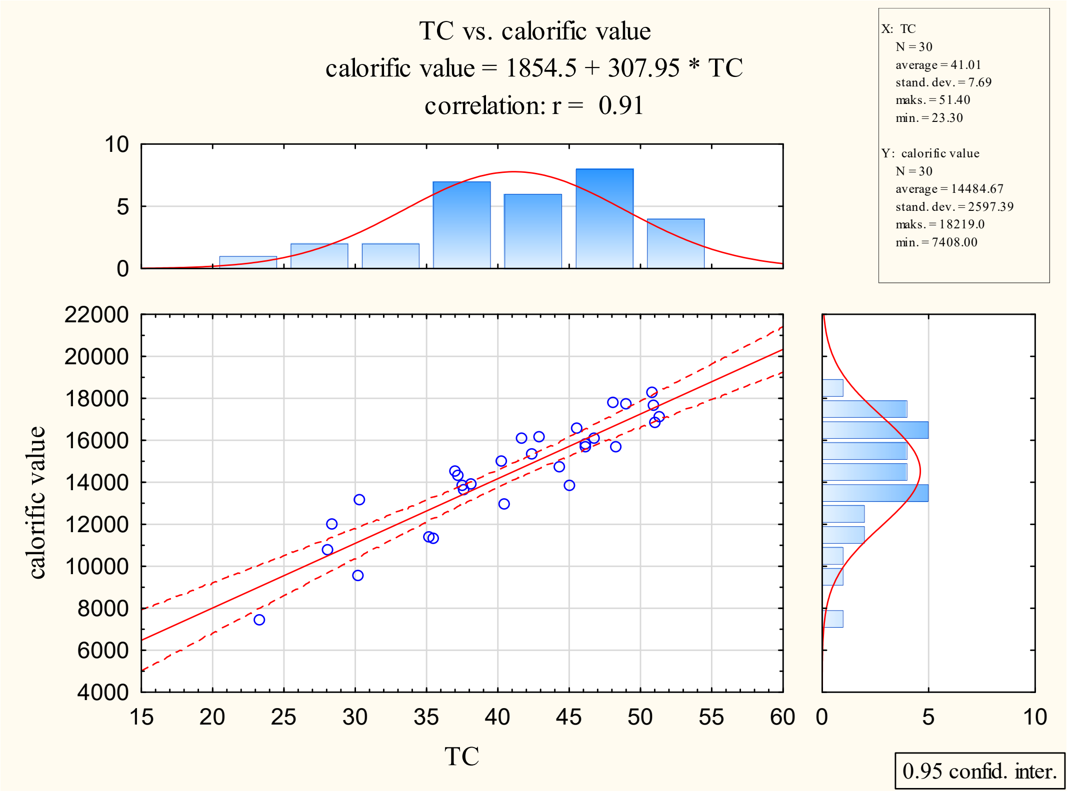


Figure 2. Graph of the correlation and dispersion of results; total carbon (TC) content vs. calorific value.

3.4. Pellet Durability Tests

After preliminary analyses of the input materials and mixtures, ten of them—the most promising ones, counting thermal properties (calorific value) and chemical composition (low heavy metal content)—were pelletized. In order to test the behaviour of the pellets under the influence of moisture, a static test was carried out – the reaction of the pellets in water and a dynamic test - the reaction of the pellets in water with mechanical mixing. Since it was expected that some of the components would be transferred into the solution, an analysis of the electrical conductivity (EC) and pH of the extracts was planned. The test results are presented in Table 5.

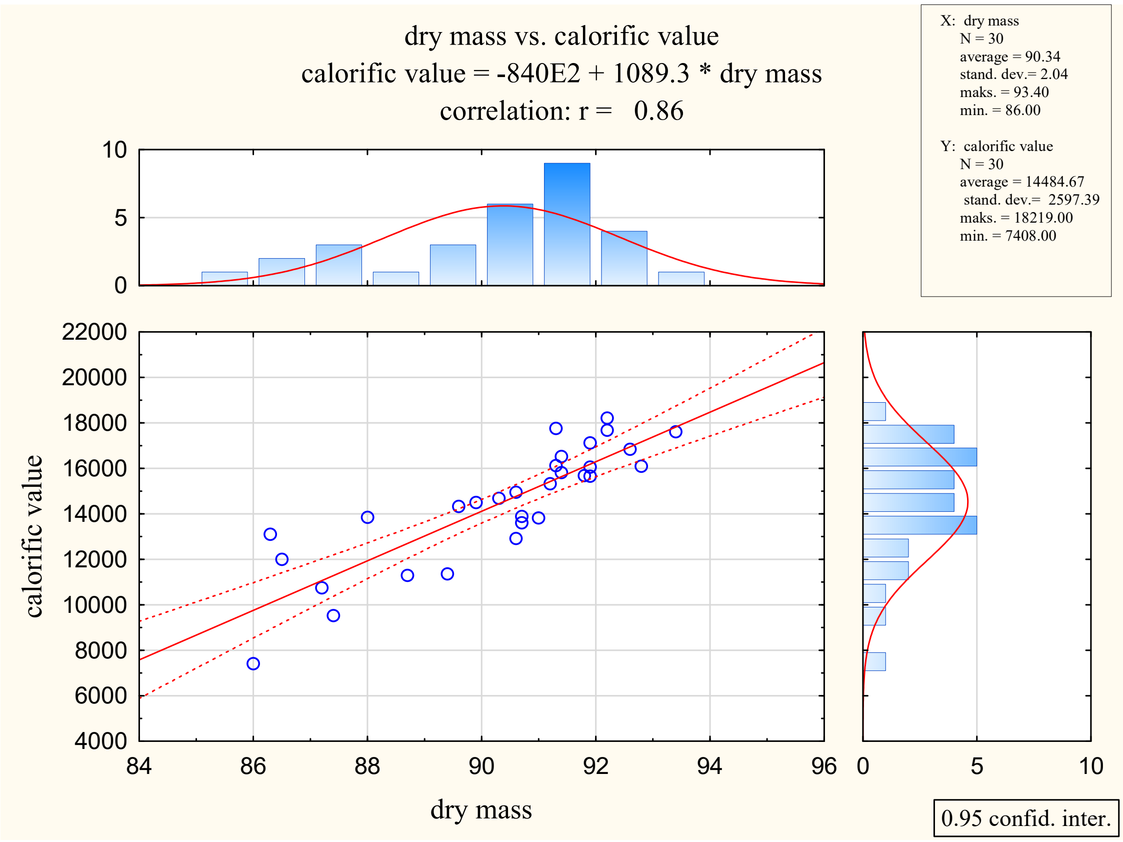


Figure 3. Graph of the correlation and dispersion of results; dry mass vs. calorific value.

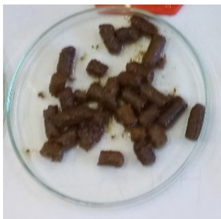
Table 5. Static and dynamic test results for pellets from the selected mixtures.

Material Designation	**Static Test: 2 d**			**Dynamic Test: 1 h Mixing 1, D Rest, 1 h Mixing**		
	Disintegration	**pH**	**EC**	**Disintegration**	**pH**	**EC**
M3	13.552 g/76 ml	12.04	12.04	14.155 g/83 ml	12.26	7.04
M10	18.516 g/68 ml	11.96	2.77	19.563 g/75 ml	11.99	6.26
M13	22.040 g/68 ml	9.48	1.98	26.049 g/68 ml	10.05	3.87
M17	30.002 g/57 ml	9.07	1.49	15.442 g/74 ml	9.51	4.00
M18	16.521 g/72 ml	11.88	2.62	15.942 g/76 ml	11.54	6.25
M19	19.249 g/72 ml	8.73	2.16	21.016 g/77 ml	9.20	3.97
M20	16.069 g/72 ml	12.12	3.05	16.372 g/81 ml	12.15	6.92
M22	16.041 g/74 ml	12.10	2.93	15.114 g/79 ml	12.17	6.89
M30	20.636 g/68 ml	12.15	2.95	15.058 g/76 ml	12.21	6.81
MD	23.245 g/65 ml	5.25	0.50	11.700 g/67 ml	5.54	0.74

Most of the pellets disintegrated under the influence of water just a few hours after being soaked. After one day, mixtures M1, M2, M4, M7, M8, M9 and M16, as well as the pellets made from the input materials WS and S, disintegrated completely.

The durability of the pellets determined in the static and the dynamic tests was the same. The most durable were the pellets from mixtures M3 (WS + SS; 1:1), M10 (WS + SS; 4:1), M18 (WS + WD + SS; 3:1:1), M19 (WS + S + SS; 3:1:1), M20 (WS + WD + SS; 6:1:3) and M22 (WS + SS; 7:3). The pellets from mixtures M17 (WS + S + SS; 7:2:1) and M30 (WS + WD + SS; 3:3:4) and from pure WD, used as the input material, retained their structure to a lesser extent. The pellets from mixture M13 (WS + SS; 9:1) lost their structure in the dynamic test but retained it in the static test. Table 6 shows the structure of the pellets after the moisture absorption tests.

Table 6. Pellet structure after the moisture absorption tests.

Static Test	Dynamic Test	Static Test	Dynamic Test
M3		M10	
			
M13		M17	
			
M18		M19	
			
M20		M22	
			
M30		MD	
			

The tests showed that the combination of wood shavings (WS) with sewage sludge (SS) was good for the pellet structure. Sewage sludge hygienized with lime acted as a binder as long as it was present in the pellets in a proportion of at least 20%. When its share was lower, 10%, i.e., in mixture M13, the stabilization effect on the WS + SS pellets decreased significantly.

When the pellets were dropped three times from a height of h = 1.5 m, the results were as follows: the pellets from mixtures M18 (WS + WD + SS; 3:1:1), M19 (WS + S + SS; 3:1:1), M3 (WS + SS; 1:1), M22 (WS + SS; 7:3), M10 (WS + SS; 4:1) and M13 (WS + SS; 9:1) did not disintegrate. For this reason, it can be said that they should be good for transport in conditions of controlled air humidity and keep their durability. In this test, the WS + SS combinations also turned out to be the most durable.

3.5. Examination of the Combustion Process in Terms of Emissions Including the Possibility of Eliminating Acid Anhydrides

Pellets prepared from mixtures M2 (WS + S; 0.5:0.5) and M17 (WS + S + SS; 0.7:0.2:0.1)—Figure 4—and from energy willow for comparison (EW) were used for the combustion analysis in the test boiler.

Figure 4. Pellets prepared from mixtures M2 and M17.

The results showed that it was possible to reduce exhaust emissions by the addition of limed sewage sludge to biomass fuel (Table 7).

Table 7. Exhaust emissions during the combustion of the fuels analyzed.

Mixture	Ash Content	Exhaust Temp.	Pressure	Flow	External Temp.	CO	NO	NO_2	NOx	H_2S	H_2
	(%)	(°C)	(hPa)	($dm^3 \cdot min^{-1}$)	(°C)	(ppm)					
M2	2.1	100	1002	0.95	28.9	310	36	0.2	34	0.8	33
M17	5.5	156	1000	0.95	29.0	144	46	0.4	42	1.5	0
WE	1.5	120	1007	0.93	24.0	139	96	1.4	97	2	13

This information on exhaust emissions makes it possible to find differences between mixture M2 (without the addition of sewage sludge) and M17 (with the addition of 10% by weight of limed sewage sludge). The results are as follows:

- reduction in CO emissions by 115%;
- increase in NO emissions by 22%;
- increase in NO_2 emissions by 50%;
- increase in NO_x emissions by 19%;
- increase in H_2S emissions by 47%;
- elimination of H_2 emissions.

The emissions of acidic anhydrides to the atmosphere from the combustion of pellets from both mixtures (M2 and M17) were lower than from the combustion of energy willow pellets:

- NO—by 63% for M2 and by 52% for M17;
- NO_2—by 63% for M2 and by 52% for M17;
- NOx—by 63% for M2 and by 52% for M17;

- H_2S—by 63% for M2 and by 52% for M17.

The decrease of CO content and the occurrence of the increased content of NO, NO_2, NO_x and H_2S in the exhaust gases was probably influenced by the burning conditions. Important elements of process disturbance could be the addition of a mineral fraction with sewage sludge hygienized with lime. The combustion of biomass pellets resulted in the accumulation of large amounts of bottom ash and slags in the combustion chambers of the boiler, which obstructed the air supply systems in the furnace over time. In literature, this phenomenon is described as a very important negative factor connected to the use of biomass for energy production [32].

In the phase of stabilized high temperature combustion, CO emissions from firewood are 250–500 ppm. Significantly higher emissions occur during the boiler warming up phase, up to 16,500 ppm, and boiler quenching, 3000 ppm. Chen et al. [38] compared the combustion of coal and sewage sludge and obtained three times less CO emissions and two times less CO_2 emissions when sewage sludge was used. This resulted in a reduction of CO and CO_2 emissions after the addition of sewage sludge to coal and a reduction of CO_2 emissions after the addition of sewage sludge to dried biomass of shiitake mushrooms. Monedero et al. [13] reported a more than 2-fold difference in CO emissions from the combustion of pellets from poplar wood (747 mg m^{-3}) and pine wood (331 mg m^{-3}). Polonini et al. [40] obtained CO emissions from the combustion of wood pellets that were similar to the emissions described in this study for M17 and EW pellets but by 40% lower than for M2. The concentration of oxygen in exhaust gases varies from 6 to 18% [37] depending on the phase. The composition of exhaust gases strongly depends on the conditions in which solid fuels are burnt, especially on combustion temperature and the primary excess air ratio. Under non-optimum conditions, e.g., when warming up a boiler, a gas with the following composition is formed: H_2, C_xH_y, H_2O, CO_2 and N_2, and NH_3, HCN, HOCN and NO in smaller amounts [10]. As a result of complete combustion, CO_2 and H_2O are formed and much more NOx. However, NOx emissions are relatively lower in comparison to wood pellets containing not much nitrogen and under optimum combustion conditions—a primary excess air ratio of 0.9–0.95 [10]. The concentration of NOx increases after the addition of sewage sludge to coal and to dried biomass of shiitake mushrooms. Monedero et al. [13] indicated that there were differences in NOx emissions depending on the type of wood that is burnt—poplar wood 229 mg m^{-3} and pine wood 97 mg m^{-3}. It is also possible to reduce CO and NOx emissions by adding calcium and magnesium compounds to poplar wood pellets—Ca,Mg-lignosulphonate. SO_2 and CH_4 emissions do not have such a clear tendency when additives from sewage sludge are used [38,43]. However, SO_2 increases after adding Ca,Mg-lignosulphonate to wood pellets [13].

4. Conclusions and Perspectives for Further Research

- The selected materials from waste biomass can be effectively used to produce energy. In perspective, pellets from wood materials mixture M1 (WS + WD; 1:1) can be a good variant of solid fuel. The addition of sewage sludge hygienized with lime (mostly mineral material) can disturb the process of biomass combustion, which resulted in incomplete fuel combustion. Wood, straw and sewage sludge mixture M17 (WS + S + SS; 7:2:1) turned out to be the best energy material prepared with the sewage sludge addition. It should be taken into account not to add more than 5% of lime to the whole fuel mixture, including the use of lime-treated sewage sludge by means of co-combustion.
- As an effect of sewage sludge addition, an increased pH and relatively high Ca, Mg, Na and Fe were found. The high potassium content was related to the construction of the material, which was solely based on straw, or the presence of straw in the mixtures. These elements will remain in the ash after the combustion of the pellets. As a result, the material rich in elements, being the desired fertilizer components, is created. Some problems can be connected with a high pH of ash (i.e., in the case of coniferous and heather cultivation) and high Ca, Mg and Na content relative to the other elements (ionic antagonism).

- Some materials containing lime-treated sewage sludge could have a relatively higher content of Cr. The evaluated situation shows the content of Cr lower than permitted by Polish law. However, the use of these materials for a long time as fertilizers may result in the accumulation of this undesirable metal in soil.
- A different problem is the durability of pellets prepared from various biomass mixtures. Wood shavings stabilized with sewage sludge hygienized with lime (mixtures M3, M13, M18, M19 and M22) are a good material for making durable pellets; from this point of view the proportion of sewage sludge in mixtures should be at least 20%.
- Due to the possible difficulties with burning a solid fuel material with a high content of mineral components, it is recommended to use mixtures M18 (WS + WD + SS; 3:1:1) and M19 (WS + S + SS; 3:1:1) for this purpose.
- The addition of sewage sludge to the biomass of M2, i.e., the production of material M17, resulted in a reduction of CO emissions and the elimination of H_2 emissions. At the same time, there was an increase in NO, NO_2, NOx, CO_2 and H_2S emissions. Further research is needed to optimize the combustion process parameters of individual biomass mixtures in terms of reducing the environmental impact of the occurring gaseous and residual products.

The combustion of waste biomass is difficult due to the highly varied composition of this fuel, both in terms of the combustion process and its environmental impact. The addition of a calcium-based mineral fraction to fuel, which is often described in the literature as effectively improving some parameters of boiler operation, is problematic, since it may cause some phenomena that are harmful to the environment. Studies should be continued to find an optimum composition of biomass mixtures to obtain a good calorific value with limited emissions of acidic anhydrides to the atmosphere. It would also be necessary to analyze how combustion technology (mainly the thermal characteristics of this process) affects the release of gases to the atmosphere in the case of fuels from pure biomass and biomass modified with lime. It should also be considered whether there is a significant difference in this respect between the addition of pure calcium carbonate and the addition of granulate from municipal sewage sludge hygienized with lime. It would also be necessary to check whether there would be any difference between the addition of municipal sewage sludge hygienized with lime in the form of granules and in the form of a non-granulated mixture.

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