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The Study of the Faba Bean Waste and Potato Peels Recycling for Pellet Production and Usage for Energy Conversion

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Abstract: The article presents the results of a study on the preparation and use of faba bean waste and potato peel pellets for energy purposes. Physical and mechanical characteristics (moisture, density, ash content) of faba bean waste and potato peel pellets were investigated. The largest fraction of flour was formed on a sieve with 1 mm holes: faba bean waste—28.2 ± 2.02 g, potato peels—29.09 ± 0.73 g. For this experiment, samples were taken by mixing faba bean waste (four variants) and potato peel in the ratio of 1:1; 1:2; 1:3; 1:4 by volume (12 samples). It was found in this study that the density of pellets (DM) ranged from 1226.22 ± 13.88 kgm^{-3} to 1349.79 ± 6.79 kgm^{-3}. The pellet moisture ranged from 6.70 ± 0.04% to 3.64 ± 0.13%. The lower calorific value of dry fuel pellets ranged from 15.27 ± 0.43 $MJkg^{-1}$ to 16.02 ± 0.50 $MJkg^{-1}$. The ash content of the pellets ranged from 8.05 ± 0.57% to 14.21 ± 0.05%. The ST temperature of the experimentally measured mixture of faba bean waste and potato peel pellets ranged from 924 to 969 °C; the DT temperature ranged from 944 to 983 °C; the HT temperature ranged from 1073 to 1202 °C, and a change in FT temperature from 1174 to 1234 °C was observed. The temperatures were sufficiently high to melt the ash. Specific emissions of CO_2, CO, NO_x and C_xH_y did not exceed the maximum levels allowed. In summary, from the results of the study of the physical properties, combustion, and emissions of waste beans and potato peel pellets (all samples), it is evident that they are used for biofuels. The combustion process of this type of pellet is characterized by efficient combustion and minimal emissions to the atmosphere.

Keywords: bean waste; pellet; potato peels; solid biofuel; calorific value; emissions

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1. Introduction

Each year, an estimated 1.3 billion tonnes of food is produced worldwide and each year, nearly a million tonnes of food is wasted for reasons such as poor food supply chain, inadequate storage, and transportation delays [1]. In 2018, the Food and Agriculture Organization of the United Nations (FAO, Quebec City, QC, Canada) estimated that 33% of human food is wasted every year [2]. Global attention to the issue of food waste, defined as inedible by-products of food production practices, is on the growth, due to economic, social, and environmental factors related to the management of these materials. The factors of food waste can be at any level between production, harvest, distribution, treatment, and consumption. Food waste has a significant detrimental effect on the environment.

The idea of Zero Waste is an effective way to tackle food waste problems so that whole foods or by-products are reused or recycled. Presently, it is popular in the world to speak about the concept of Zero Waste. Zero Waste Europe offers a prescription for food waste prevention: the first step for better food waste control; food distribution and redistribution of unsold and unnecessary food. When food cannot be eaten, it should be handled according to a waste hierarchy, such as composting, biofuel, or similar. Agro-industrial waste is considered to be one of the most preferred sources of renewable energy because it can provide sustainable energy and is environmentally friendly. The use of agricultural residues can also reduce environmental pollution.

The idea of sustainable development consists of three parts: economic, social development, and environmental protection. However, an important argument for the use of biomass waste is the limited and depleted land resources. It is therefore important to use waste, but not agricultural products, thus contributing to the circular economy. One way to use agricultural vegetable waste or mixtures is to convert them into solid fuels (pellets, briquettes). However, according to many researchers [3], obtaining high quality pellets is difficult because it is influenced by many factors, such as density, humidity, calorific value, and harmful emissions. All these indicators must meet certain requirements and standards [4].

Many scientists in the literature have described their research with various biomasses, such as bark, wheat straw and rapeseed straw [5], olive mills [6], mixtures of peel and fruit peel, waste from the palm industry [7], rapeseed flour waste biomass, maize stover, barley straw [8], and many others. The most important properties of granules are their durability, which can be effected by humidity, size, binders, granulation conditions and temperature.

Faba beans are grown all over the world in systems such as grains and legumes. Faba beans contribute to the sustainability of growing systems through their ability to introduce nitrogen into the system through their ability to biologically fix N_2, diversification of systems, leading to a reduced incidence of diseases, weeds, and pests. Due to the increased efficiency of fertilizers used in plants, the sowing of forage beans has increased recently due to their role as a nitrogen source for future growing systems [9]. Faba bean waste has high biomass residues, ranking from 3.7 to 5.7 t ha^{-1} and accounting for 42–51% of total harvest biomass. Pellets made from bean waste have good properties to be used as biofuels. The lower calorific value of dry fuel obtained from faba bean waste pellets was 17.1 MJ kg^{-1} [10].

A lot of waste is also generated during potato processing. In the preparation of potato products, about 35–46% of the recycled mass becomes waste. It has been established that in Europe, the volume of potato pulp; the main by-product of potato starch production, can reach 1 million tonnes per year [11]. Potato waste, without proper handling, is the cause of many pests: potato leaf roll virus, late blight, ring rot, etc. Potatoes contain a variety of nutrients: up to 24% starch, 2% plant proteins, enzymes, various nutrients, organic and mineral salts. The high content of potato farina allows treating the pulp as a pre-pelleting binder additive to plant materials that are described by a lower sensibility to densification. Researchers have studied potato pulp and mixtures of potato pulp with other plant waste (buckwheat husk, oat bran) and found that the pellets have high energy properties. The heat of combustion of potato pulp pellets in dry matter is 16.33 MJ kg^{-1}, and the calorific value is 15.41 MJ kg^{-1} [12,13].

According to the Statistics Lithuania, the production of potatoes and legumes in 2019 exceeded 337.1 and 301.5 thousand tonnes, respectively [14].

When developing new solid biofuels, physical and chemical indicators must be analysed. These indicators are important for the transportation, storage, and combustion of biofuels.

Prior to the granulation process, it is appropriate to prepare the material by cutting and grinding to achieve the finer fraction of the flour, as the density of biofuels will depend on the quality of the flour [15]. Pellet density and moisture are significant indicators of fuel quality. These indicators are directly related: the higher the humidity, the lower the density [16]. The moisture content of biomass also has a significant effect on the total calorific value [17]. When developing new biofuels (liquid or solid), many researchers are looking for a compromise between heat combustion and harmful emissions [18]. This compromise encourages research to look for fuels that can provide the required calorific value at lower emissions [19,20].

The aim of the study is to investigate the solid mixture of biofuels (pellets) produced from potato peels and faba bean waste, to assess the biometric features and physical-mechanical parameters, to determine the quality indicators of grinding, granulation and use of this waste for combustion, as well as to determine harmful gas emissions from the combustion of biofuel pellets from these wastes.

2. Materials and Methods

2.1. Raw Material Preparation and Sampling

Potato peel samples were collected from food production companies in Lithuania. The potato peels were cut into small pieces and cleaned with water, then dried naturally until a constant weight was reached.

The faba bean waste used for the pellet production was taken after cutting, harvesting, and threshing the beans grown in Lithuania, at the VMU AA Experimental Station. Samples of faba bean do not need drying [21].

For this experiment, samples were taken by mixing faba beans flour (three variants) and potato peels flour with the proportion of 1:1 (A); 1:2 (B); 1:3 (C) and 1:4 (D) by volume (Table 1).

Table 1. Sample collection and composition.

No	Sample	Composition	Ratio Potato: Beans
1	1 mix A	Faba beans from the field with deep soil ploughing and potato peels	1:1
2	1 mix B		1:2
3	1 mix C		1:3
4	1 mix D		1:4
5	2 mix A	Faba beans from the field with deep soil loosening and potato peels	1:1
6	2 mix B		1:2
7	2 mix C		1:3
8	2 mix D		1:4
9	3 mix A	Faba beans from the field with uncultivated soil and potato peels	1:1
10	3 mix B		1:2
11	3 mix C		1:3
12	3 mix D		1:4

2.2. Determination of Mill Quality, Density, Moisture Sontent and Biometric Properties of Pellets

In order to use the prepared faba bean and potato waste for the production of pellets, they were milled with a mill "Retsch SM 200" to particles with a diameter of 0.1–2.0 mm [21].

The quality of grinding was determined from the weight fraction recorded using a Retsch AS 200 sieve shaker (sieves with holes: 0, 0.25, 0.5, 0.63, 1 and 2 mm). The remaining weight on the sieves was estimated and the percentage of each sample was calculated for each fraction. The container with the meal was weighed, and the flour weight and density were calculated.

The moisture content of the flour was determined in the chemical laboratory of Vytautas Magnus University, according to a standard method. Twelve samples were taken randomly, weighed, and dried over 24 h, then the samples and empty containers were weighed again, and the moisture content of each sample was calculated. The moisture contents of biomass, chaff, and granules were put in a percentage [22].

A low-capacity (100–120 kg/h) pelletizer with a horizontal matrix was used for the production of biofuel from bean and potato skin waste. Its diameter is 6 mm. The biometric properties of the granules were determined by size, moisture, volume, and density [22].

Having registered the size (diameter, length, and weight) of the granules, the volume and density (balance accuracy 0.01 g) were calculated [21].

2.3. Elemental Composition, Calorific Value, Ash Content and Emissions of the Pellet Burning

The elemental composition, energy value, ash content, and emissions of the produced beans and potato peel granules were studied in the Lithuanian Energy Institute (LEI, Kaunas, Lithuania), according to the standard method prevailing in Lithuania and other European countries: measurement of total O_2, CO, CO_2, NO_x and SO_2—in accordance with the requirements and by the standards of the Ministry of Environment of the Republic of Lithuania (Vilnius, Lithuania) [23–25]; ash handling unit—according to LST EN 14775:2013 [24]; calorific value—according to the standard [26] and UNIEN 14918 [27], respectively.

In order to determine the concentrations of harmful gas emissions, studies were performed at the Lithuanian Energy Institute, Thermal Equipment Research and Testing Laboratory. Pellet samples (5 kg) were used for burning in a low-power solid fuel boiler (5 kW), and emission tests were performed. Combustion of each sample took 8–10 min. The amounts of total carbon, hydrogen, nitrogen, sulphur, and oxygen formed during combustion were measured with a "Datatest 400CEM" combustion product analyser, according to the standards "LAND 43-2013. Norms for combustion plants emissions" [28] and "LST EN 303–5:2012. Heating boilers. Part 5" [29]. After the determination of harmful gas emissions into the environment, these results were compared with similar indicators found by other researchers.

Ash melting temperature characteristics were determined using a Carbolite CAF furnace, according to the ASTM D 1857 method. According to the ASTM standard, the ash cone shape change during combustion in a specific oxidizing environment is divided into the following phases: the starting point of deformation (IT)—the sharp peak is rounded; softening point (ST)—the ash cone is deformed: the height of the structure is reduced to the size of its diameter; hemispheric temperature (HT)—the sample takes the form of a hemisphere, and its height is equal to half the diameter of the base; melting point (FT)—the ash melts, liquefies and spreads over the plate [30].

The study data were statistically evaluated using one factor analysis of variance [31]. The ANOVA program was used to determine the boundaries of the basic difference between the probability levels R05 and R01 [30]. SigmaStat and SYSTAT programs were used for correlation analysis.

3. Results

3.1. Characteristics of Samples

The three variants with best results of faba bean waste flour were taken from the previous study: variant 1—from the field with deep soil ploughing, variant 2—from the field with deep soil loosening, and variant 3—from the field with uncultivated soil [10]. For this experiment, samples were taken by mixing faba bean (three variants) and potato peels at the ratios of 1:1; 1:2; 1:3; 1:4 by volume. Subsequently, the flour volumes of faba bean waste, potato peels and their mixtures were weighed, and the density of the mixtures was determined. The results are presented in Table 2.

Table 2. Flour ratio and density of faba bean and potato waste samples.

No.	Sample	Ratio	Potato Weight, g	Faba Bean Flour Weight, g	Total Sample Mass, g	Total Sample Volume, m^3	Density, kg m^{-3}
1	1 mix	1:1	920	448	1368	0.004	342.00
2	1 mix	1:2	477	466	943	0.003	314.33
3	1 mix	1:3	464	670	1134	0.004	283.50
4	1 mix	1:4	469	890	1359	0.005	271.80
5	2 mix	1:1	937	506	1443	0.004	360.75
6	2 mix	1:2	490	475	965	0.003	321.67
7	2 mix	1:3	449	681	1130	0.004	282.50
8	2 mix	1:4	481	879	1360	0.005	272.00
9	3 mix	1:1	969	483	1452	0.004	363.00
10	3 mix	1:2	491	516	1007	0.003	335.67
11	3 mix	1:3	471	770	1241	0.004	310.25
12	3 mix	1:4	475	953	1428	0.005	285.60

The highest flour density was in three samples with a ratio 1:1, where the weight of potato peel flour was the highest.

3.2. Determination of Fineness of Flour Prepared for Granulation

The fineness of grinded raw materials of faba bean and potato waste flour affects the quality of the pellets, such as density and resistance to compression. Pellets are made from several different flour mix variants, so the moisture content may vary.

Fractional composition analysis of crushed bean waste and potato peel (Figure 1) showed that most of the flour accumulated on sieves with a hole diameter of 1.0 mm: flour from bean waste—28.2 ± 2.02%, and flour from bean waste—28.2 ± 2.02%, potato peel—29.09 ± 0.73% (relatively large fraction). A large fraction of flour was also found on a sieve with holes with a diameter of 0.5 mm: faba bean waste flour—21.98 ± 1.2% and potato peel flour—25.49 ± 0.38%. The smallest fraction collected on a sieve with a hole diameter of 2.0 mm: flour from bean waste—15.61 ± 1.94% and flour from potato peel—7.51 ± 0.5%.The content of fine particles—dust (0.25 and 0 mm)—was also fairly high, ranging from: faba bean waste flour—from 17.98 ± 0.82% to 16.23 ± 0.66% and potato peel flour—from 17.44 ± 1.95% to 20.47 ± 1.99%.

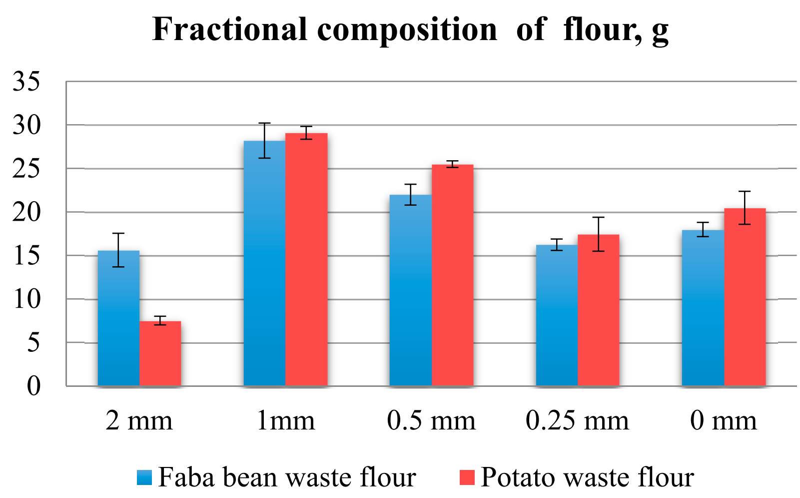

Figure 1. Fractional composition of faba bean and potato peel flour.

The study of the flour fraction showed that the distribution of flour particles is suitable for granulation.

3.3. Designation of the Biometric Properties of Granules

ISO 17829 standard for solid biofuels specifies that the diameter of the pellets must be 6.0 ± 1.0 mm or 8.0 ± 1.0 mm, and the length—3.15 < L ≤ 40 mm [32]. The results of biometric and other pellet properties are presented in Table 3.

The most important parameters of the granules were determined by measuring them during the production of pellets. Dimensions were measured with a digital calibre with a resolution of 0.01 mm. Bulk density is the ratio of the mass of pellets to the total volume of granules. It is a basic parameter for treatment, storage, and transportation facilities. It depends on the particle size and shape of the biomass, the particle density, and the moisture content [33].

Strength is related to the density of pellets. Pellets have to withstand high loads and forces during storage, transportation, and delivery to the burning implements. Moreover, a significant amount of small particles (dust) may be produced, which does not ensure normal combustion quality and leads to increased emissions. Increased energy density per unit volume and homogeneous structure allow better control of the combustion process, thus increasing the efficiency of energy production and reducing emissions of combustion products. By standard, the pellet density limit value is from 1000 kg m^{-3} to 1400 kg m^{-3}.

In this study, the density of pellets (DM) was found to range from 1226.22 ± 13.88 kg m^{-3} (3mixC) to 1349.79 ± 6.79 kg m^{-3} (2mixB). It can be stated that these pellets meet the standard and are of good quality for transportation.

Table 3. Biometric properties of pellets.

Sample	Moisture Content, %	Length, mm	Diameter, mm	Weight, g	Volume, m^3	Density, kg m^{-3}	Density, kg m^{-3} (DM)
1 mix A	4.96 ± 0.10	21.56 ± 0.34	6.02 ± 0.01	0.83 ± 0.02	$6.14 \times 10^{-7} \pm 0.11 \times 10^{-7}$	1345.15 ± 7.64	1278.43 ± 6.50
1 mix B	5.68 ± 0.05	21.51 ± 0.11	6.14 ± 0.02	0.89 ± 0.01	$6.37 \times 10^{-7} \pm 0.06 \times 10^{-7}$	1403.26 ± 10.98	1323.55 ± 9.26
1 mix C	6.20 ± 0.17	19.98 ± 0.43	6.02 ± 0.02	0.78 ± 0.02	$5.68 \times 10^{-7} \pm 0.14 \times 10^{-7}$	1384.67 ± 20.37	1298.82 ± 17.09
1 mix D	6.47 ± 0.11	21.03 ± 0.40	6.02 ± 0.01	0.80 ± 0.01	$5.98 \times 10^{-7} \pm 0.11 \times 10^{-7}$	1345.14 ± 7.62	1258.11 ± 6.38
2 mix A	3.64 ± 0.13	17.74 ± 0.13	6.13 ± 0.02	0.73 ± 0.01	$5.24 \times 10^{-7} \pm 0.06 \times 10^{-7}$	1393.30 ± 3.76	1342.58 ± 3.24
2 mix B	4.39 ± 0.88	19.76 ± 0.18	6.13 ± 0.02	0.82 ± 0.01	$5.82 \times 10^{-7} \pm 0.06 \times 10^{-7}$	1411.77 ± 7.94	1349.79 ± 6.79
2 mix C	3.79 ± 0.11	21.18 ± 0.19	6.07 ± 0.01	0.82 ± 0.01	$6.13 \times 10^{-7} \pm 0.07 \times 10^{-7}$	1333.35 ± 10.69	1282.82 ± 9.20
2 mix D	6.14 ± 0.14	20.70 ± 0.05	6.03 ± 0.01	0.81 ± 0.01	$5.90 \times 10^{-7} \pm 0.02 \times 10^{-7}$	1369.89 ± 12.36	1285.78 ± 10.38
3 mix A	4.60 ± 0.03	19.51 ± 0.27	6.08 ± 0.01	0.75 ± 0.01	$5.66 \times 10^{-7} \pm 0.09 \times 10^{-7}$	1322.94 ± 5.48	1262.08 ± 4.68
3 mix B	4.87 ± 0.02	20.95 ± 0.31	6.08 ± 0.02	0.84 ± 0.01	$6.08 \times 10^{-7} \pm 0.09 \times 10^{-7}$	1381.13 ± 4.58	1313.87 ± 3.90
3 mix C	5.78 ± 0.25	20.67 ± 0.23	6.02 ± 0.01	0.77 ± 0.02	$5.88 \times 10^{-7} \pm 0.06 \times 10^{-7}$	1301.44 ± 16.47	1226.22 ± 13.88
3 mix D	6.70 ± 0.04	20.58 ± 0.13	6.03 ± 0.01	0.77 ± 0.01	$5.87 \times 10^{-7} \pm 0.03 \times 10^{-7}$	1310.91 ± 6.72	1223.08 ± 5.61

In his study with potatoes, S. Obidziński found that the density of granules ranged from 1105.96 kg m^{-3} to 1314.87 kg m^{-3} and depended on the moisture content [13]. In a subsequent study by S. Obidziński with potato and buckwheat husk pellets, their density ranged from 841.71 kg m^{-3} to 1234.86 kg m^{-3} and depended on the amount of potatoes in the mixture [4].

Determination of the biometric characteristics of faba bean waste and potato peel pellets resulted in a correlation. A weak correlation between density and moisture and a moderate correlation between the amount of potato peel in the pellets and their moisture content was obtained (Table 4).

Table 4. Correlation between moisture content and potato peel content in pellets.

Indicator	Moisture Content, %	Density, kg m^{-3}	Potato Peel Content, %
Moisture, %	1	*n*	*n*
Density, kg m^{-3}	−0.25	1	*n*
Potato peels content, %	−0.65	0.25	1

n—weak correlation.

Many scientists have investigated and confirmed that the moisture content of pellets is a key factor in determining the amount of energy in biomass and how it affects calorific value and combustion efficiency [34–36]. This is one of the main indicators of pellet quality.

Results (Figure 2) showed that the moisture content of faba bean waste and potato peel pellets changed from 3.64 ± 0.13% (2mixA) to 6.70 ± 0.04% (3mixD). According to ISO 18134, the moisture content of the granules must not exceed 10%. The pellets obtained do not exceed this value [33].

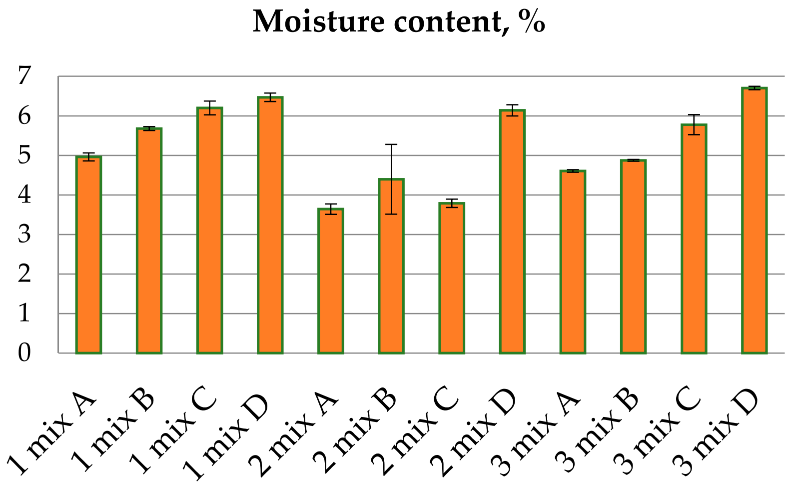

Figure 2. Moisture content of pellets, % (proportions of potato and beans: 1:1 (A); 1:2 (B); 1:3 (C); 1:4 (D) by volume).

3.4. Determination of the Elemental Composition Properties of Faba Bean Waste and Potato Peel Pellets

These investigations showed that faba bean waste and potato peel pellets consist of three main components: carbon (C), hydrogen (H), oxygen (O), which taken together account for 84–90%. These results do not differ from wood pellets (Table 5).

Table 5. Elemental composition properties of pellets.

Component	1 Mix A	1 Mix B	1 Mix C	1 Mix D	2 Mix A	2 Mix B	2 Mix C	2 Mix D	3 Mix A	3 Mix B	3 Mix C	3 Mix D
C, %	40.49 ± 0.97	42.74 ± 0.86	43.06 ± 0.24	43.86 ± 1.01	42.14 ± 0.82	43.02 ± 0.05	42.97 ± 0.54	42.60 ± 2.32	42.24 ± 2.39	42.16 ± 0.72	41.52 ± 1.35	43.70 ± 0.31
H, %	6.30 ± 0.05	6.30 ± 0.05	6.30 ± 0.05	6.30 ± 0.05	5.21 ± 0.05	6.30 ± 0.05	6.30 ± 0.05	6.30 ± 0.05	6.30 ± 0.05	6.30 ± 0.05	6.30 ± 0.05	6.30 ± 0.05
N, %	1.79 ± 0.62	2.28 ± 0.46	0.45 ± 0.27	0.32 ± 0.25	2.33 ± 0.45	1.79 ± 0.54	1.61 ± 0.45	1.78 ± 0.59	1.53 ± 0.45	2.14 ± 0.44	1.63 ± 0.64	1.52 ± 0.45
S, %	0.13 ± 0.09	0.18 ± 0.12	0.10 ± 0.09	0.08 ± 0.05	0.11 ± 0.09	0.14 ± 0.09	0.12 ± 0.09	0.07 ± 0.02	0.08 ± 0.02	0.13 ± 0.02	0.13 ± 0.02	0.12 ± 0.09
O, %	38.76 ± 0.00	38.18 ± 0.00	38.52 ± 0.00	38.78 ± 0.00	38.33 ± 0.00	37.07 ± 0.00	40.96 ± 0.00	39.01 ± 0.00	36.89 ± 0.00	35.07 ± 0.00	36.25 ± 0.00	35.87 ± 0.00
Cl, %	0.21 ± 0.05	0.22 ± 0.06	0.26 ± 0.06	0.26 ± 0.06	0.27 ± 0.06	0.25 ± 0.05	0.26 ± 0.06	0.25 ± 0.05	0.28 ± 0.07	0.29 ± 0.07	0.30 ± 0.08	0.32 ± 0.09

Additionally, in other studies the content of carbon (C), hydrogen (H) and nitrogen (N) in the pellets was: nipa palm: C—40.19%, H—6.73%, N—0.55% [37], rape straw: C—43.46%, H—4.91%, N—1.14% [3], rice husk: C—38.13%, H—6.03%, N—0.66% [38] and this shows that the amounts of carbon (up 40.49 ± 0.97% to 43.86 ± 1.01%), hydrogen (up 5.21 ± 0.05% to 6.30 ± 0.05%) and nitrogen (up 0.32 ± 0.25% to 2.28 ± 0.46%) in the faba bean and potato peel pellets do not differ significantly compared to other pellets from agricultural plant waste.

3.5. Determination of Energy Value, Ash Characteristics and Harmful Emissions

Comparing the calorific values of the studied plant waste pellets with the calorific values of other agricultural plants and their waste, it can be seen that the energy value of bean and potato peel waste is very similar to grass waste: raw rice straw—14.75 MJ kg^{-1} [39], Felina 32—17.37 MJ kg^{-1} [40], rice husk and wheat straw mix—15.44 MJ kg^{-1} [41], tea waste—17.39 MJ kg^{-1}, oil palm empty fruit bunch—16.74 MJ kg^{-1} [42], vine pruning and corn stover mix—15.06 MJ kg^{-1} [43].

The calorific value of lower dry fuel pellets ranged from 15.27 ± 0.43 MJ kg^{-1} (3mixB) to 16.02 ± 0.50 MJ kg^{-1} (1mixD) (Figure 3). According to S. Obidziński, the calorific value of potato pellet was 15.41 MJ kg^{-1} [13] and the calorific value of the mixture of buckwheat husks and potato pulp increased from 17.9 MJ kg^{-1} to 17.9 MJ kg^{-1} when the amount of potatoes used in the mixture was 10–30% [4]. It was determined that the calorific value of faba bean pellets can reach 17.00 MJ kg^{-1} [10], and the buckwheat husk pellets can reach a very high value—18.89 MJ kg^{-1} [4]. After the comparison of calorific values, it can be stated that these thermal properties directly depend on the proportion of potatoes in the granules. The lower the proportion of potatoes, the higher the caloric value of the pellets.

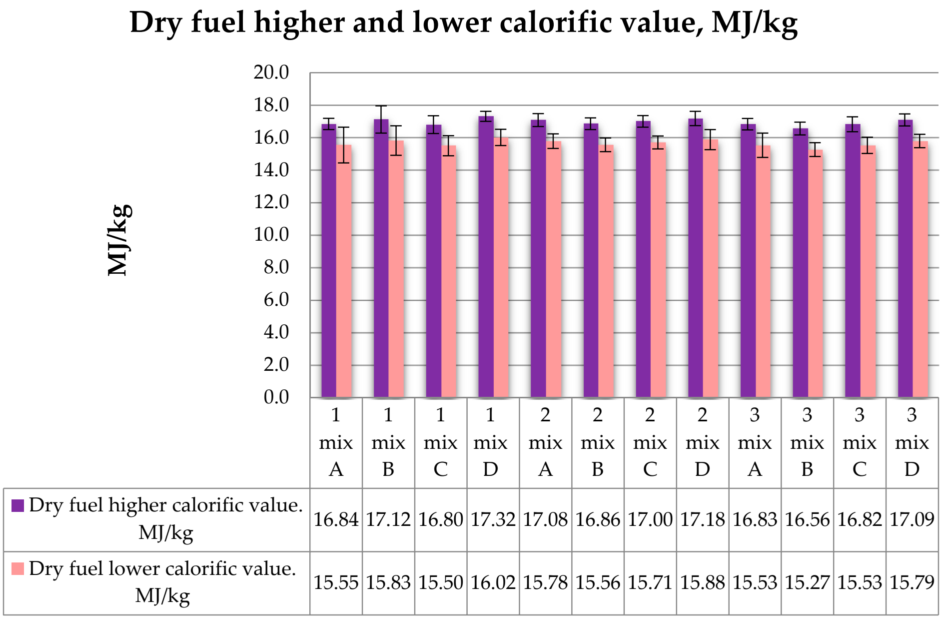

Figure 3. Calorific value of faba bean and potato peel pellets (proportions of potato and beans: 1:1 (A); 1:2 (B); 1:3 (C); 1:4 (D) by volume).

After an analysis of the results of other researchers, it can be observed that the calorific value of biomass depends mainly on the content of carbon, hydrogen, sulphur, nitrogen, oxygen, and ash. The author, Noorfidza Yub Harun, found that when biofuel pellets have low nitrogen content, these low nitrogen values can increase the calorific value of the granules [36]. In this case, the correlation coefficient (r = 0.20) shows a low correlation between the nitrogen content and the calorific value of pellets.

The pellet ash index measures the amount of ash remaining after the pellets have been burned. High ash content degrades fuel quality [43]. The ash content in the 12 variants studied ranged from 8.05 ± 2.57% (2 mix C) to 14.21 ± 0.05% (3 mix B) (Figure 4).

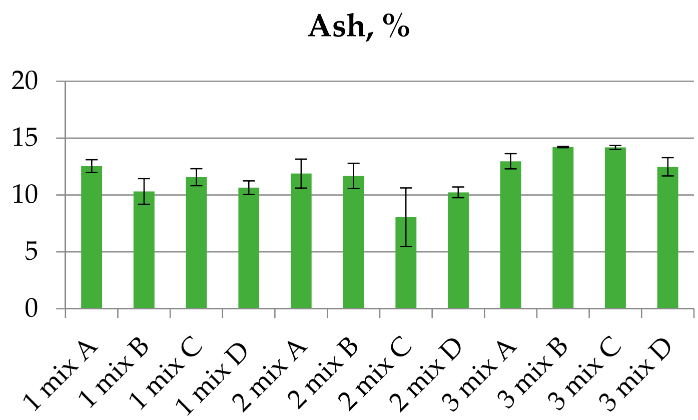

Figure 4. The ash content from the combustion of biofuel pellets (proportions of potato and beans: 1:1 (A); 1:2 (B); 1:3 (C); 1:4 (D) by volume).

The determined ash content, after the burning of plant waste pellets, is higher than that of wood pellets, so it requires a combination of the combustion process of granulated biofuels and ash removal. Comparing the results obtained by other researchers with plant pellets, it was concluded that the results differ little. For example, rice straw pellets contained 12.03% of ash, palm kernel shell—10.67% [44], corn straw—10.0%, grapevine residue—13.3% [45].

Ash melting characteristics are well-known parameters that describe the melting point of biofuels and the effect of ash melting [46]. According to CENT/TS 15370-1, the shape changes of the ash samples were evaluated to determine the following ash fusion characteristics: softening temperature (ST), initial deformation temperature (DT), hemisphere formation temperature (HT), and liquid formation temperature (FT) [47–49].

The determined melting temperatures of the pellet ash are shown in Figure 5 and Table 6. The highest ash softening temperature (ST) in the sample was found to be 2mixD —969 °C and the lowest was 2mixB, 924 °C. The highest primary ash deformation temperature (DT) was that of 2mixD, 983 °C, and the lowest one was that of 2mixB, 944 °C. The highest ash hemisphere formation temperature (HT) was in sample 3mixC, 1202 °C, and the lowest—1mixB, 1073 °C. The ash fusibility temperature (FT) fanged from 1174 °C (2mixC) to 1234 °C (3mixB) (Figure 5).

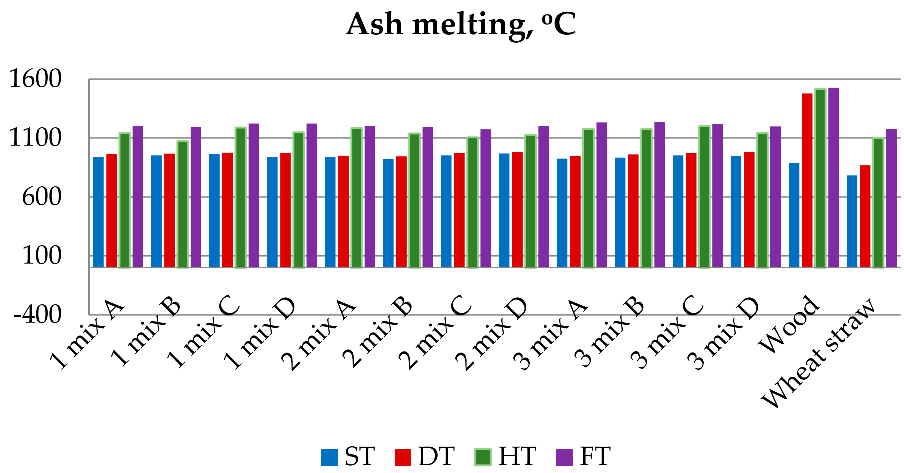

Figure 5. Ash melting temperatures of plant waste pellets (proportions of potato and beans: 1:1 (A); 1:2 (B); 1:3 (C); 1:4 (D) by volume).

Table 6. Ash melting temperatures of plant and wood pellets.

Sample	ST, °C	DT, °C	HT, °C	FT, °C	Reference
Wood	888	1477	1514	1526	[48]
Wheat straw	783	869	1099	1175	[48]
Miscanthus sinensis	877	923	1254	1286	[49]
Dactylis glomerata	1065	1128	1186	1206	[49]

Comparative analysis with the results obtained by other authors (Table 6) showed that the melting point of ash is similar to that of other plant pellets but lower than wood. This is important when choosing the combustion technology and the combustion mode of the furnace.

3.6. Harmful Environmental Emissions from Burning of Pellets

The use of energy and agricultural plants and their residues as an environmentally friendly fuel for energy production is directly related to its benefits, e.g., the renewable form can reduce the amount of CO_2-neutral waste [50,51].

The values of harmful emissions from the burning of plant biomass must comply with the requirements set by the standards approved by the Ministry of the Environment of the Republic of Lithuania [24–26].

The values of carbon dioxide, carbon monoxide, oxygen, nitrogen oxides and unburned hydrocarbons were evaluated. The results of harmful gas emissions from burning agricultural plant waste pellets are presented in Figures 6–8. Data from wood pellets were taken for comparison.

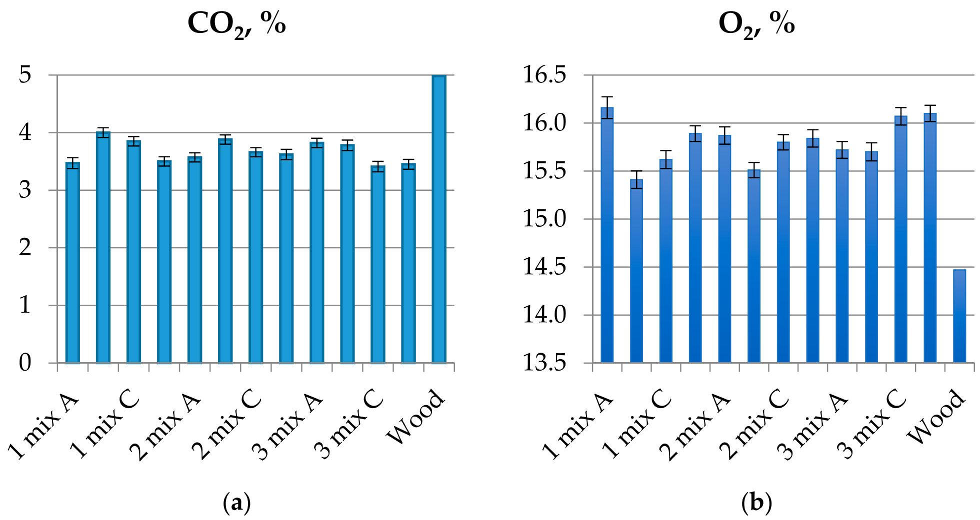

Figure 6. CO_2 (**a**) and O_2 (**b**) emissions from burning of granulated faba bean waste and potato peels.

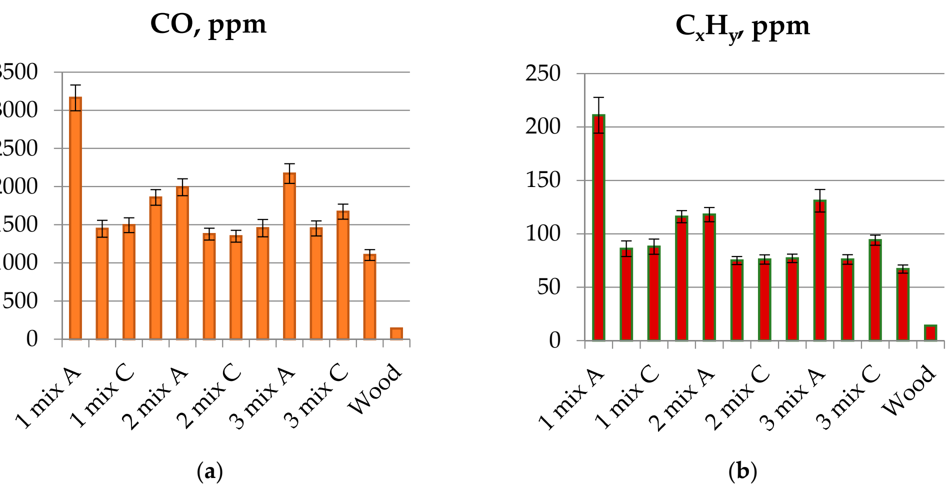

Figure 7. CO (**a**) and CxHy (**b**) emissions from burning of granulated faba bean waste and potato peels.

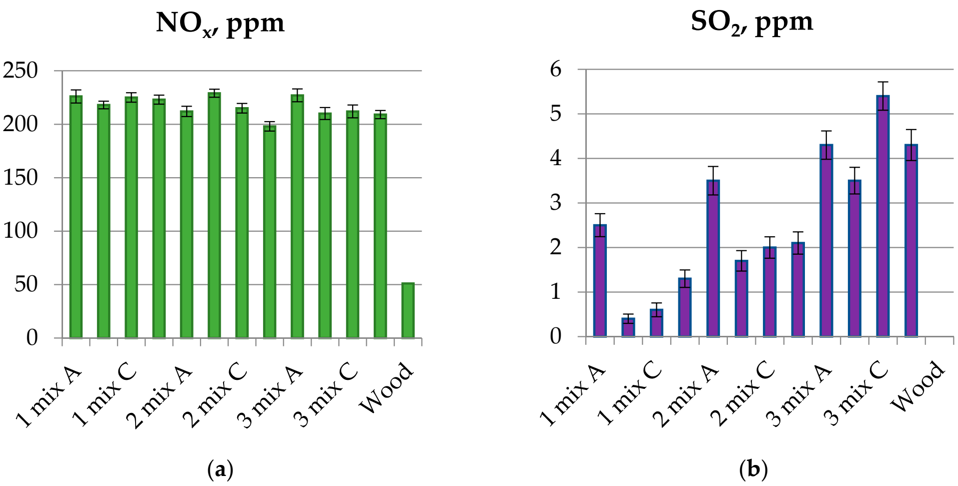

Figure 8. NO_x (**a**) and SO_2 (**b**) emissions from burning of granulated faba bean waste and potato peels.

From the obtained results, it was found that the CO_2 emissions directly depend on the oxygen content in the fuel (Figure 6). The correlation coefficient was 0.96. The determined carbon dioxide emissions were lower than those of wood pellets.

It can be observed that the CxHy level is similar to that obtained with CO emissions (Figure 7). It can be assumed that this is influenced by the incomplete combustion of the pellets (correlation coefficient—0.99).

According to O. Sippula, fuels with higher nitrogen content have higher NO_x emissions [52]. The correlation between the nitrogen content of the pellets and the burning NO_x emissions is equal to 0.36 (weak relationship). SO_2 concentrations range from 0.5 ppm (1mixB) to 5.4 ppm (3mixC), and they are insignificant. The highest SO_2 content was found in all variant 3 samples from the field with uncultivated soil (Figure 8).

Researchers, A. Jasinskas, J. Ahirwal and Z. Qiuguo, find that the quality of biomass depends on soil composition and cultivation method, which can be observed in this study [10,52,53].

Pellets of this type are of sufficiently high quality and have efficient combustion and minimal environmental pollution, so these investigated pellets can be used for biofuel.

4. Discussion and Conclusions

Scientists around the world are increasingly looking at the use of agro-waste for solid biofuels. This work also analyses the new product and its properties for use in energy conversion.

Twelve pellet variants were made from faba bean and potato peels. Physical and chemical properties of the granules were comprehensively studied and determined: density, moisture, ash content, calorific value, elemental composition, and measured emissions of granules.

The flour fraction has a significant effect on the production of pellets. The largest fraction of flour was formed on a sieve with 1 mm holes: faba bean waste—28.2 ± 2.02 g, potato peels—29.09 ± 0.73 g. The largest amount of flour was concentrated in holes up to 1 mm and accounted for up to 84.4% of faba bean waste flour and up to 92.5% of potato peel flour. The fractional composition of this mill is suitable for granulation and does not require additional grinding.

The length and diameter of the granules corresponded to the standard. The highest density of pellets was determined for the sample 2mixB—1349.79 ± 6.79 kg m^{-3}, and the lowest—1226.22 ± 13.88 kg m^{-3}—3mixB. These pellets meet the biometric-physical characteristics of the standard and do not require additional materials or operations to increase the density.

The lower calorific value of dry fuel pellets ranged from 15.27 ± 0.43 MJ kg^{-1} (3mixB) to 16.02 ± 0.50 MJ kg^{-1} (1mixD). The lower calorific value of the dry pellets corresponds to the indicators of other pellets of plant biomass and depends on the amount of potato peel in the pellets.

After determining the ash content in the pellets, it was found that the least ash was formed by burning 2mixC sample pellets—8.05 ± 0.57%, and the highest ash content was found in the sample 3mixB—14.21 ± 0.05%. Comparing all the pellet samples tested, the worst indicators were in variant 3 (all mixtures). These indicators were influenced by soil composition and the tillage method [10].

The ST temperature of the mixture of experimentally measured faba bean waste and potato peels reaches 924–969 °C, the DT temperature reaches 944–983 °C, the HT temperature reaches 1073–1202 °C, and the FT temperature is the highest and reaches even 1174–1234 °C.

The results of the harmful emissions investigated show that the CO_2 content directly depends on the oxygen content of the fuel and was up by 3.41 ± 0.09% in the 3mixC sample and by 4.00 ± 0.08% in the 1mixB sample. The C_xH_y emission level was similar to that obtained with CO emissions. C_xH_y emissions ranged from 67 ± 3.77% (3mixD) to 211 ± 16.76% (1mixA), CO—1103 ± 71.31 ppm (3mixD) and 3163 ± 169.52 ppm, accordingly (1mixA). The SO_2 concentration ranges from 0.5 ppm (1mixB) to 5.4 ppm (3mixC) and is found to be insignificant. The NO_x emissions were found to be the lowest in the sample 2mixD (198 ± 4.39 ppm) and the highest in the sample 2mixB (229 ± 3.78 ppm).

In summary, the results of the preparation and use of faba bean waste and potato peel pellets (all samples) show that they can be used for biofuels that are of a sufficient quality, have efficient combustion, and are low in pollutant emissions. For the production of pellets, this raw material of waste must be properly prepared and granulated: however, potato peels are usually too wet for granulation and require additional energy for drying.

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