INVESTIGATION OF PHYSICAL-MECHANICAL AND ENERGY PROPERTIES OF GRANULATED CEREAL PLANT WASTE AND ASH OBTAINED BY INCINERATION OF PRODUCED BIOFUEL

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Abstract. The world's population grows, so people need food. As the food demand increases, so does the demand for cereals. Lithuania is one of such countries where cereals are grown in abundance. After removing the grain, the received grain crop waste – straw may be used for a variety of purposes by farmers. Straw can be used as litter, left in the fields to rot as fertilizer, and straw can be used as a renewable energy source. For some time now, there has been talk of using straw as a solid biofuel, but not much research has been done to investigate the physical-mechanical and energy properties of such sort of straw biofuel – pellets. The aim of the study was to investigate the physical-mechanical, thermal, energy and other properties of barley and wheat cereal straw pellets and ash obtained from their burning. Pine sawdust pellets were also studied for comparison. Investigations of pellet quality showed that pressed granules are of high quality and density. The highest density pellets were obtained by pressing wheat straw – 985.2 ± 81.5 kg·m^{-3} DM (dry matter), and the lowest – by pressing pine sawdust (896.3 ± 26.1 kg·m^{-3} DM). Studies have shown that 5.65% of ash are released from barley straw pellets burning, 5.60% - from wheat straw pellets burning, and, after pine sawdust pellets burning, the ash content reached 0.54%. Research results of thermal properties showed that the calorific value of barley straw pellets was slightly higher than that of wheat straw pellets – for barley straw it reached 18.45 MJ·kg^{-1}, and for wheat straw – 18.54 MJ·kg^{-1}. However, the calorific value of cereal straw pellets is lower than that of wood sawdust pellets – the calorific value of pine sawdust pellets was reached even 20.51 MJ·kg^{-1}. Studies of harmful emissions (CO_2, NO_x, CO, C_xH_y) during pellet burning were also investigated, and the results obtained showed that emissions do not exceed the permissible limits. Summarizing the results of the research, it can be stated that in order to improve the thermal and energy properties of straw biofuel pellets, it is expedient to mix straw with wood sawdust.

Keywords*:* straw pellets, wheat, barley, physical-mechanical purposes, energy purposes, emissions.

Introduction

The energy sector is important for every country, especially for countries that do not have significant fossil fuel resources. Lithuania is a small country with very limited fossil fuel resources, so ways to increase the countr's energy independence are constantly being sought for. One of the most popular alternative energy sources in Lithuania is biofuel: a raw material produced from biomass waste [1]. Biomass includes: wood, its harvesting and processing waste; agricultural crops and their waste; livestock waste (manure); organic waste from the food industry; organic fractions of municipal waste, etc. [2].

Agriculture is intensively developed in Lithuania. Although the country is dominated by less fertile soils, large quantities of cereals are grown here. 2019 the total amount of grain grown in Lithuania amounted to 5.129 million t. Growing such large quantities of grain leaves a large amount of by-products, *i.e.* straw. The fuel potential of straw biomass is the largest potential of plant waste in the country, reaching 850 thousand tons [3].

About 15-20% of the total amount of straw is left in the fields as fertilizer, up to 20% is collected and used for litter and feed, about 1% of straw is used for other purposes. Data of statistics show that more than 50% of straw remains unused [4; 5].

One of the main advantages of using straw for heat production is that straw contains a high proportion of hemi-cellulose and less lignin, which makes straw cells less resistant to tension and compression [6]. It is also worth mentioning that during the transportation of straw pellets 5-10% losses as part of the granules decompose into flour [7].

Straw can be used to produce heat, electricity or heat and electricity. Analysis of information sources show that by burning straw electrical efficiency can be achieved by about 30%, while heat efficiency can reach up to 70-80% [8]. The energy value of straw is 16.3 MJ·kg^{-1}, and, for comparison, that of wood is 18.0 MJ·kg^{-1} [9]. Comparing the energy values of different types of straw, the highest energy values are for flax straw (17.8 MJ·kg^{-1}), maize stalks (17.7 MJ·kg^{-1}), barley and rye straw

(17.5 MJ·kg^{-1}), and the lowest energy values are for triticale straw and rapeseed stalks (17.1 MJ·kg^{-1}) [10].

Carbon, hydrogen, sulfur, oxygen and nitrogen in the compounds contained in straw fuel form the flammable (organic) part. In addition to flammable elements, straw contains a little part of potassium, sodium, chlorine, phosphorus, silicon and very few other elements that remain in the ash after straw burning. The ash content of straw is high compared to wood fuel. When burning straw and wood, about 3-5% and 0.5-2% of ash can be formed respectively [11; 12]. Straw ash contains about 0.09% nitrogen, 1% phosphorus, 11% potassium, and there are small amounts of copper, zinc, tin, nickel, chromium, *etc*. Due to this composition, ash can be used as fertilizer and spread in the fields, it does not need to be utilized as wood ash [11]. It should be mentioned that the melting point of straw ash ranges from 800 to 1000 ºC [13]. According to [12], the melting temperature of wheat straw ash reaches 1400 ºC, rye – 1330 ºC, barley – 1190 ºC, oats – 1175 ºC.

Straw as a raw material for heat production can be used by pressing into rolls, producing briquettes and pellets. Storing straw bales requires large storage areas, so it is more promising to prepare briquettes or pellets from straw. Also, the production of pellets and briquettes allows to compact straw from 150-250 kg·m^{-3} to 600 kg·m^{-3} and more Thus, increasing the amount of energy per unit volume and reducing the necessary storage areas, makes biofuels easier to handle, transport, and more resilient to physical environmental factors [14-17].

The use of straw in Lithuanian energy sector is extensive, which means that it is used exclusively for heat production. Straw is burned in relatively small boiler houses, and the obtained energy is used to heat small buildings. Lithuania does not have a developed system for straw collection and use in larger boiler or cogeneration power plants [18].

Not much research has been done to show that straw is a viable fuel for heat production. So, extensive research is needed to substantiate this.

The aim of this research – to investigate the physical-mechanical and energy properties of grain crop residue (straw) pellets and to evaluate the emissions of harmful substances.

Materials and methods

Methods for determination of biometric indicators, fractional composition, physical-mechanical and energy properties of straw pellets

Research investigations of preparation and use of straw pellets for burning was carried out in 2018-2020 in the laboratories of the Vytautas Magnus University Agriculture Academy, Institute of Agricultural Engineering and Safety, and the Lithuanian Energy Institute. For preparation of pellets, the bundles of straw were chopped with a drum chopper and milled with a hammer mill into flour with a fineness of 1-2 mm. For production of 6 mm diameter pellets, a small capacity granulator "Peleciarka" (*Polemix*, Poland) was used.

Three types of granules were used for the research:

- Barley straw pellets;
- Wheat straw pellets;
- Pine sawdust pellets (control sample).

Pine sawdust pellets were used to compare the parameters of straw pellets.

The density of the produced biofuel granules was determined by measuring the length and diameter of the granules. With these two parameters, the granule volume is calculated, and with further volume, the granule density is found analytically. 10 granules of each plant species were tested.

Moisture content of straw and wood sawdust pellets, calorific value, ash content and ash melting temperatures were performed according to the standardized methodology valid in Lithuania and the European countries, by using these devices:

- humidity tester – in accordance with the requirements of the standard LST EN 14774-1: 2010;
- ash testing device – in accordance with the requirements of LST EN 14775: 2010 standard;
- calorific value testing device, C 2000 calorimeter (IKA, Germany) – in accordance with the requirements of the standard LST EN 14918: 2010;

- ash melting temperatures were determined according to LST CEN/TS 15404.

Determination of harmful gases emissions to the atmosphere

Biofuel pellet burning quality and harmful emissions greatly influenced the type and quality of biofuel, and the type of furnace in the boilers. These investigations were carried out in a solid-fuel boiler of 5 kW power.

The studies of harmful gas emission concentrations were performed at the Lithuanian Energy Institute, Thermal Equipment Research and Testing Laboratory. The pellet samples (5 kg) were used for combustion, and emission testing was performed. The combustion of each sample took 7–10 min. The amounts of total carbon, hydrogen, nitrogen, sulfur and oxygen formed during combustion were measured with combustion product analyzers: Datatest 400CEM and VE7. All these measurements were done according to the requirements of the standards LST EN 303-5: 2012 and LAND 43-2013. After determination of the harmful gases emissions into the environment, these results were compared to the indicators of other sorts of biofuel pellets, produced from herbaceous plants: Elephant grass (*Miscanthus*), Sida (*Sida hermaphrodita*) and Reed canary grass (*Phalaris arundinacea*) [19].

All experiments were repeated 3–5 times. The obtained research data were evaluated by the methods of variance and correlation-regression analysis. Arithmetic means, their standard deviations and confidence intervals at the probability level of 0.95 according to P criterion were determined [20; 21].

Results and discussion

Moisture tests were performed on barley, wheat and pine sawdust pellets. The results of pellet moisture content tests are presented in Figure 1. The tests of pellet moisture content showed that the highest (11.18 ± 2.20%) moisture was that of pine sawdust, and the lowest (8.82 ± 2.0%) – of barley straw pellets. For comparison, the moisture content of wheat straw pellets was 9.02 ± 2.00%.

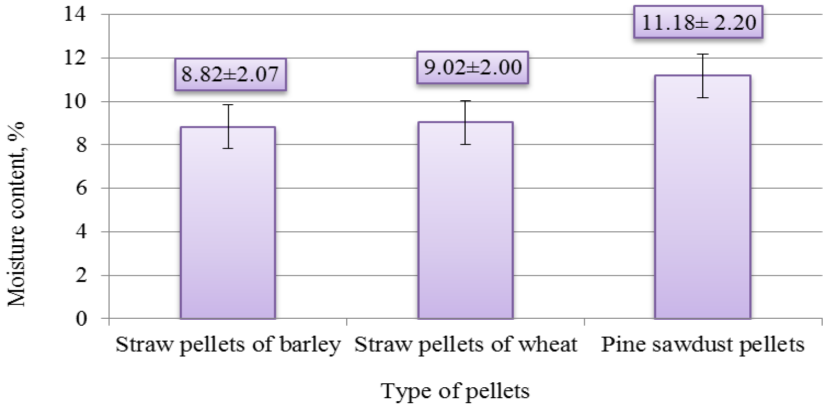

Fig. 1. **Moisture content of pellets**

Investigations of biometric and physical-mechanical properties of barely straw, wheat straw and pine sawdust granules have shown that properly prepared flour fractions and pressed granules are of high quality and density. Pellet density is an important indicator for pellet transportation and storing. The highest density pellets were obtained by pressing wheat straw – 985.2 ± 81.5 kg·m^{-3} DM (dry matter), and the lowest density pellets were produced from pine sawdust – 896.3 ± 26.1 kg·m^{-3} DM.

Ash analysis was performed for pellets of all three species (barley, wheat and pine sawdust). The results of the ash content studies are presented in Figure 2.

The results of ash content studies showed that the highest (5.65 ± 0.40%) ash content was formed by burning barley straw pellets, and the lowest (0.54 ± 0.34%) by burning pine sawdust pellets. The ash content of wheat straw pellets was very close to the ash content of barley straw pellets and amounted to 5.60 ± 0.54%. Studies of ash melting temperatures showed that the highest (1275 ± 0.28 ºC) ash melting temperature (FT) was of pine sawdust pellets. The results of ash melting characteristics are given in Table 1.

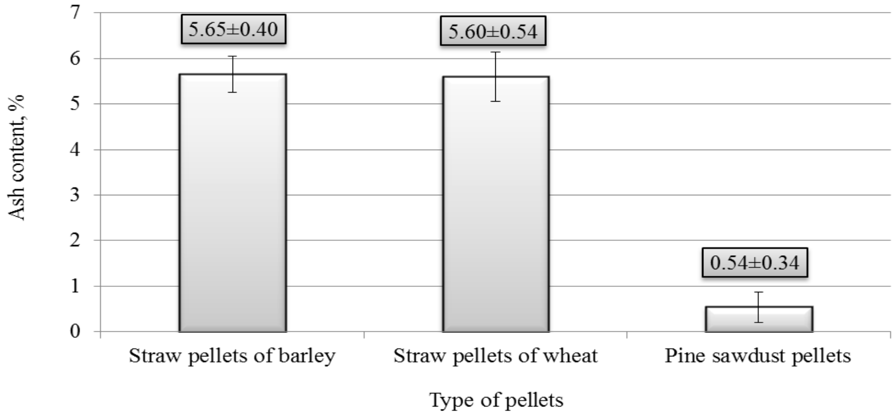

Fig. 2. **Ash content of pellets**

Table 1

Straw and pine sawdust ash melting characteristics

Plant sort	**Values of ash melting characteristics, ºC**			
	ST	DT	HT	FT
Barley straw	882 ± 0.98	909 ± 1.52	1058 ± 1.66	1166 ± 1.22
Wheat straw	985 ± 2.12	1034 ± 1.95	1145 ± 3.10	1198 ± 2.08
Pine sawdust	1211 ± 0.64	1225 ± 0.75	1250 ± 0.68	1275 ± 0.28

The softening of pine sawdust ash (ST) begins at a temperature of 1211 ± 0.64 ºC, and the initial point of deformation of ash (DT) is 1225 ± 0.75 ºC. These temperatures are sufficiently high. The melting temperature of the ash of barley (FT) straw pellets reaches 1166 ± 1.22 ºC, the initial point at which the ash begins to soften (ST) is low, and reaches 882 ± 0.98 ºC, and the deformation of the ash (DT) begins at 909 ± 1.52 ºC. The ash melting temperature of wheat straw pellets (FT) reaches 1198 ± 2.08 ºC, the ash begins to soften (ST) at 985 ± 2.12 ºC, and the deformation of the ash (DT) begins at 1034 ± 1.95 ºC. The high ash softening and melting temperature indicates that the boiler will not clog the slag so quickly, so pine sawdust pellets are the most acceptable fuel of all three cases studied. And also for pellet production could be recommended to use the mixtures of pine sawdust and straw flour.

The studies of pellet dry matter calorific value were performed. The results of the lower calorific value studies are presented in Figure 3.

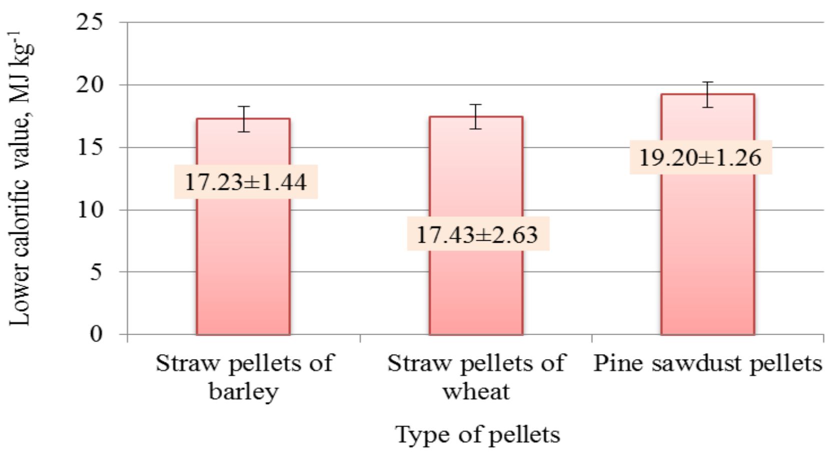

Fig. 3. **Lower calorific value of pellets**

The highest (19.20 ± 1.26 $MJ \cdot kg^{-1}$) lower calorific value was obtained from pine sawdust pellets, and the lowest (17.23 ± 1.44 $MJ \cdot kg^{-1}$) – from barley straw pellets. The lower calorific value of wheat straw pellets was very similar to barley straw pellets and reached 17.43 ± 2.63 $MJ \cdot kg^{-1}$.

For comparison of thermal properties of non-traditional energy plants [19], we can to state that the lower calorific value of Elephant grass, Sida and Reed canary grass pellets was very similar to straw pellets and varied from 17.4 $MJ \cdot kg^{-1}$ to 17.8 $MJ \cdot kg^{-1}$.

For determination of harmful emissions, three types of pellets were burned: barley straw, wheat straw and pine sawdust. Concentrations of CO_2, NO_x, CO, C_xH_y were determined. The results of harmful CO_2 emissions are presented in Figure 4.

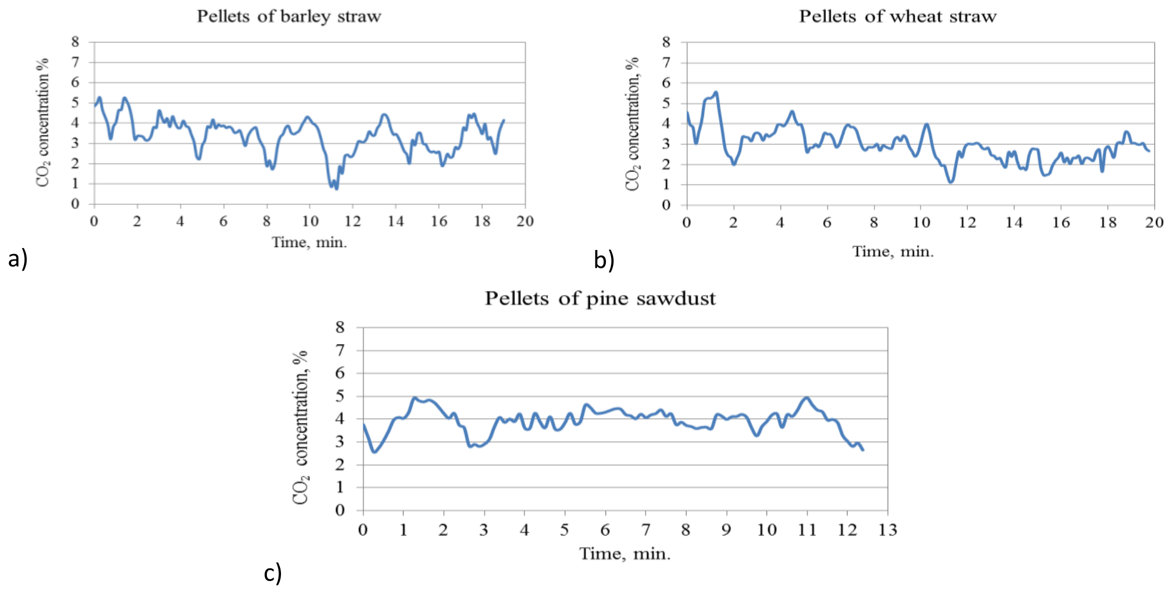

Fig. 4. **Carbon dioxide (CO_2) emissions from burning different types of pellets:**
a – barley straw pellets; b – wheat shoot pellets; c – pine sawdust pellets

The emission limit values for combustion of energy plants are regulated by the rates of combustion plants, approved by the Minister of Environment of the Republic of Lithuania [22]. These norms regulate limit values for harmful emissions from biofuels, including herbaceous plants and straw. Here defined emission limit values for new biofuel boilers with a thermal input 0.12-1.0 MW are as follows: SO_2 – 2000 $mg \cdot Nm^{-3}$; NO_x – 750 $mg \cdot Nm^{-3}$ and particulate matter – 800 $mg \cdot Nm^{-3}$.

Limited CO emissions for manual and automatic loading of solid fuel heating boilers with a thermal input of up to 500 kW are presented in the other standard [23]. According to the requirements of this standard, the following the norms of CO emission are allowed for boilers with automatic loading: 3000 for 3rd class and 1000 for 4th class.

Figure 4 shows that the combustion of different types of pellets resulted in uneven and highly fluctuating combustion. When burning wheat pellets, the highest CO_2 concentration was about 5.5%, barley – 5.3% and pine sawdust – 5%.

The following average emissions of harmful gases were determined during the combustion of wheat straw pellets: carbon dioxide CO_2 – 3.38%; carbon monoxide CO – 845 ppm, nitrogen oxides NO_x – 91.59 ppm and unburnt hydrocarbons C_xH_y – 65.65 ppm.

Very similar average emissions of harmful gases were detected during the combustion of barley straw pellets: carbon dioxide CO_2 – 3.38%; carbon monoxide CO – 649.09 ppm, nitrogen oxides NO_x – 134.83 ppm and unburnt hydrocarbons C_xH_y – 40.28 ppm.

The following average values of harmful pollutant emissions were determined during the combustion of pine sawdust pellets: carbon dioxide CO_2 – 3.92%; carbon monoxide CO – 341.38 ppm, nitrogen oxides NO_x – 128 ppm and unburnt hydrocarbons C_xH_y – 18.27 ppm.

For comparison there were analyzed and compared the results of emissions of other research investigations, when burning various non-traditional energy plants, such as Elephant grass, Sida and Reed canary grass (Sakalauskas et al., 2014). It was determined that the highest concentration of carbon monoxide (CO) was found when burning of Elephant grass – 2294.7 $mg \cdot m^{-3}$, and the lowest concentration of CO, when burning of Reed canary grass – 905.2 mg·m^{-3}. For comparison, these CO emissions during burning of wheat and barley straw pellets were lower.

Emissions of sulfur dioxide SO_2 were not detected during combustion of various types of energy plants. The highest amount of carbon dioxide was determined by burning Sida – 7.9 mg·m^{-3}, and the lowest amount of CO_2 was obtained by burning Elephant grass – 5.2 mg·m^{-3} [19]. Very similar results were obtained when burning of wheat and barley straw pellets (5.5 and 5.3%). The results of studies on burning pellets and assessing emissions from nitrogen oxides NO_x show that they do not exceed the permissible levels. The determined emissions of nitrogen oxides differed slightly, ranging from 176.2 mg·m^{-3} (Reed canary grass) to 216.1 mg·m^{-3} (Elephant grass) [19]. The determined NO_x emissions, when burning investigated straw pellets, were lower.

It has been established that the emissions of CO_2, NO_x, CO, C_xH_y into the environment, when burning straw pellets, were not too high, and they do not exceed the permissible limits.

Conclusions

1. Lithuania is not rich in fossil fuels, so it is very important to find alternatives to firewood. Large amounts of straw are formed in the country. Part of straw is used, but about 60% of the entire amount remains in the fields and is ingested. So, straw could be one of alternatives to biofuel.
2. The research results of pellet moisture content and density showed that the highest moisture was that of pine sawdust (11.18 ± 2.20%), and the lowest (8.82 ± 2.07%) – of barley straw pellets. The highest density of pellets were obtained by pressing wheat straw – 985.2 ± 81.5 kg·m^{-3} DM (dry matter), and the lowest – from pine sawdust (896.3 ± 26.1 kg·m^{-3} DM).
3. Burning of barley, wheat and pine sawdust pellets showed that the ash content of barley was 5.65 ± 0.40%, wheat – 5.60 ± 0.54%, and pine sawdust – 0.54 ± 0.34%.
4. The performed ash melting temperatures showed that the highest (1275 ± 0.28 ºC) ash melting temperature is that of pine sawdust pellets, and the lowest (1166 ± 1.22 ºC) – of barley straw pellets. The ash melting temperature of wheat straw pellets reached 1198 ± 2.08 ºC.
5. The lower calorific value studies showed that the calorific value of pine sawdust pellets was the highest (19.20 ± 1.26 MJ·kg^{-1}), and the lowest (17.23 ± 1.44 MJ·kg^{-1}) – of barley straw pellets, although the calorific value of wheat straw pellets (17.43 ± 2.63 MJ·kg^{-1}) was close to the calorific value of barley straw pellets.
6. Studies on harmful emissions to the environment (CO_2, NO_x, CO and C_xH_y) from the combustion of pellets have shown that the values obtained do not exceed the permissible limit values specified in the standards.

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