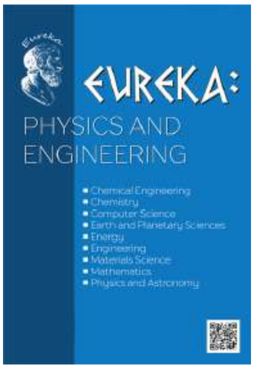

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RESEARCH AND ANALYSIS OF CHARACTERISTICS OF FUEL FROM ORGANIC AND INDUSTRIAL WASTE

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Abstract

The article is devoted to the actual problem of utilisation of agricultural and industrial waste as a solution to the problem of replacing traditional energy sources.

As an alternative fuel, researchers suggest using briquettes from biomass (leafy debris, waste paper, sunflower and buckwheat husks), as well as their combination with industrial waste (coal dust). The choice of these sources of raw materials is determined by their presence in the north-eastern part of Republic of Kazakhstan.

Studies of the physical and mechanical and thermophysical characteristics of fuel briquettes from organic mass and bio-charcoal briquettes were carried out. The studies showed the following results: the moisture content of the samples we studied lies in the range from 3.86 to 8 %; ash content of briquettes from vegetable raw materials varies from 2.05 % to 3.6 %, combined briquettes from foliage and coal dust varies from 10 % to 14 %; average density values varies from 979.91 to 1172.63 kg/m^3; mechanical strength is in the range from 90 to 100 %; the yield of volatile studied samples ranges from 9 to 21.4 %. Analysis of the obtained characteristics of fuel briquettes demonstrated that they meet the requirements of existing standards. Herewith, the lower calorific value of briquettes (15290–19048 kJ/kg) is comparable to the calorific value of coal from the Ekibastuz deposit.

The authors studied the influence of the parameters of the briquetting process on the briquette's strength characteristics from leaves and waste paper, and obtained a regression dependence of these briquette's calorific value on their characteristics. The analysis of regression dependencies showed that the pressure and pressing time have the greatest influence on the briquette strength, and its composition, i.e., the ratio of leaves and waste paper in the feedstock, has the greatest influence on the lower calorific value.

Keywords: renewable energy, biomass, raw material, fuel briquettes, organic waste, compression pressure, characteristics, calorific value, strength, volatile matter.

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1. Introduction

Due to the obvious changes in climate over the past decades and the consequences of this change, it is necessary to take active actions to solve this problem. At this stage in the development of the world community, the transition to a low-carbon economy is one of the actual issues on the global agenda of states and corporations.

In this regard, Republic of Kazakhstan is no exception, therefore the Government of the country has prepared a doctrine of carbon neutrality, which is designed to help to reduce greenhouse gas emissions by 2060 to almost zero levels [1]. In accordance with this plan and the «Concept for the transition of the Republic of Kazakhstan to the «green economy» [2], it is necessary to solve the problem of increasing the use of low-carbon fuels. The share of alternative and renewable electricity should reach 50 % by 2050.

The search and finding of renewable energy and raw material resources that could compete with coal, oil and natural gas has been going on for a long time. Plant biomass, due to such basic qualities as renewability, environmental friendliness in comparison with other types of fuels, lack of impact on the balance of free carbon in the atmosphere, is considered one of the most «noble» types of fuel and observed in many countries as a promising source of energy for the near future. For these purposes, vegetable waste can be used in its pure form [3], using a binder [4, 5] and pre-heat treatment [6], as well as in combination with coal dust [7]. The use of a binder and heat treatment of raw materials improves the strength and operational properties of briquettes, makes them compact and convenient for transportation, but at the same time complicates the process of manufacturing briquettes and increases their cost due to the use of additional devices and energy sources. Fuel based on vegetable raw materials without additives and a binder, or with the addition of waste during the extraction and use of solid fuel – coal dust, seems to be economically viable.

The most technologically advanced solid biofuel made from renewable biomass is pellets and briquettes. Briquetted solid fuels are easy to manufacture and are produced mainly from wood processing and agricultural waste (including livestock), as well as from household waste. And this is important, since, in addition to the energy problem, it allows simultaneously solving waste disposal issues [8].

One of the possible sources of raw material source for the production of fuel briquettes is foliage. Briquettes from leaves flare up well, are distinguished by long combustion, they can release from 8.8 to 17.7 MJ [9, 10] of energy per 1 kg of briquette, which exceeds the thermal power of dry firewood, oil shale and peat.

According to our estimates, the potential of falling leaves, for example, in Pavlodar (Republic of Kazakhstan) is at least 4.5 thousand tons per season. With the calorific content of fuel briquettes from fallen leaves of 19000 kJ/kg, the energy potential of fallen leaves for the season in Pavlodar will be 85500 GJ.

If considering agricultural waste, then the choice of raw materials for briquettes depends on the availability of waste in each specific region of the world and can be used: sugarcane cake, sisal, cassava bran [11]; dried banana leaves [9]; rice husks and bran [12]; sugarcane leather, bamboo fiber [13]; vine shoots, peel, stems and seeds of grapes [14]; corn [15]; areca leaves [4]; coffee husks, soybean husks, wheat and rice straw, jute, mustard, cotton stalks, coconut pith, tobacco waste, peanut seed shells [16].

Waste generated during the cultivation of crops such as wheat, rye, oats, barley, millet, rice, buckwheat, corn, sunflower, rapeseed, lint can be considered as agricultural raw materials for the production of bio briquettes in our country. As of January 1, 2021, 12 678 077 tons of grain and legumes were produced, as well as 1 430 724 tons of oilseeds [17].

The methodology described in [18] was used to determine the waste available for energy production and to assess its energy potential. Calculations showed that the waste of grain and legumes amounted to 7 987 188.5 tons, oilseeds – 231 177.3 tons. The total energy content of agricultural waste is 417 098.2 thousand of GJ.

The use of these briquettes in the housing and communal services of small urban settlements makes it possible to effectively use local types of resources and reduce the adverse impact on the environment. There is experience of using fuel briquettes on low-power boilers. With a small difference in the calorific value of coal and fuel briquettes, the efficiency of boilers when using fuel briquettes reaches 51.83 %, which is 5.28 % higher than that of coal (46.55 %). Equivalent fuel consumption per 1 GJ of generated heat: coal – 0.073 tons of equivalent fuel/GJ, fuel briquettes – 0.066 tons of equivalent fuel/GJ [19].

Analysis of the Republic of Kazakhstan market for fuel briquettes showed that the volume of their production and use is insignificant. Attention should also be paid to the absence of such types of organic waste as leaves, buckwheat and sunflower husks in the raw material base of existing industries. The aim of our study was to determine the characteristics of briquettes from these types of waste and the possibility of their further energy use.

2. Materials and methods

2. 1. Selection of raw materials and the process of making briquettes

For research, briquettes were made from organic waste: leaves (**Fig. 1, *a***), leaves and waste paper in the following ratios: 40/60, 50/50, 60/40; 90/10; 100/0 (**Fig. 1, *b-e***), sunflower husks (**Fig. 2, *a***), sunflower husks and starch in a 2:1 ratio (**Fig. 2, *b***), buckwheat and cellulose husks in a 2:1 ratio (**Fig. 2, *c***), bio-coal briquettes from foliage and coal of the Ekibastuz basin in various ratios: 50:50, 60:40, 70:30, 80:20, 90:10 (**Fig. 3**).

a *b* *c* *d* *e*

Fig. 1. Briquettes from organic matter (ratio of leaves : waste paper):
a – 40:60; *b* – 50:50; *c* – 60:40; *d* – 90:10; *e* – 100:0

a *b* *c*

Fig. 2. Agricultural waste briquettes:
a – sunflower husks; *b* – sunflower husks and starch (2:1); *c* – buckwheat and cellulose husks (2:1)

a *b* *c* *d* *e*

Fig. 3. Bio-coal briquettes of foliage and coal of the Ekibastuz basin (leaves : coal ratio):
a – 50:50; *b* – 60:40; *c* – 70:30; *d* – 80:20; *e* – 90:10

The technological process for the manufacture of fuel briquettes consisted of the following stages:

– cleaning of raw materials from foreign inclusions (glass, plastic, metal, etc.);

– drying raw materials in the open air to an air-dry state;

– crushing raw materials to a size of no more than three millimetres;

– preparation of a mixture of water with crushed waste (for briquettes from leaves and waste paper) until a homogeneous mass is obtained;

– loading into a press and pressing fuel briquettes at a pressure of 25 MPa;

– drying the obtained fuel briquettes in the room to an air-dry state.

In the manufacture of briquettes, the compression pressure, the holding time under pressure and the pressing temperature were varied.

2. 2. Determination methods for the main characteristics of fuel briquettes

In the work, the mechanical-and-physical and thermophysical characteristics of fuel briquettes were determined.

The moisture content of the obtained briquettes was determined in accordance with GOST R 54186-2010 EN 14774-1:2009. Solid biofuels. Determination of moisture content by drying. The essence of the method consists in drying a sample of briquettes in a drying oven at a temperature of 103 ± 2 °C and calculating the weight loss of the sample taken.

In accordance with the procedure described in GOST R 55661-2013 ISO 1171:2010. Solid biofuels. Determination of ash content, depending on the initial composition of the raw material, the ash content of the obtained briquettes was determined. The essence of the method consists in ashing a sample of briquettes in a muffle furnace and calcining the ash residue for two hours in a closed muffle furnace at a temperature of 800±25 °C. After cooling and weighing, the change in mass is determined.

The main factor that determines the mechanical strength, water resistance and calorific value of the briquette is its density, which was determined in accordance with GOST 32987-2014. Solid biofuels. Determination of bulk density. The essence of the method: a standard container of a specified size (volume 5 or 50 litres) and molds are filled with a sample with compaction of bulk material due to impact and weighed. The bulk density is calculated from the net weight and the internal volume of the container. To determine the mechanical strength of briquettes, the standard GOST R 55111-2012 EN 15210-2:2010 Solid biofuels. Determination of the mechanical strength of pellets and briquettes was used. Drum sample is a method for assessing the strength of fuel briquettes, which consists in mechanical processing of particles in a rotating steel drum and subsequent determination by sieve analysis of changes in the particle size distribution of the sample [20].

To determine the volatile matter substances according to GOST 32990-2014 EN 15148:2009. Solid biofuels. Determination of the volatile matter, a muffle furnace with a thermostat, a thermocouple, a firepot with a lid, a desiccator with granular calcium chloride, a laboratory balance with a weighing error of no more than 0.1 mg and a stopwatch were used. The release of volatile matter is defined as the sample mass loss of solid fuel minus moisture when heated without air access under standard conditions.

The essence of the determination method for the calorific value and the calculation of the calorific value of briquettes is the complete combustion of a sample of the test fuel mass in a calorimeter bomb in an isothermal mode at a constant volume in the medium of compressed oxygen under the pressure of $29{,}4 \cdot 10^5$ Pa (30 kgf/cm^2) and measuring of the water temperature in the calorimeter vessel, as well as in determining the corrections for the heat released during the combustion of the fire wire and the heat of formation and dissolution of sulfuric and nitric acids in water.

2. 3. Modelling the influence of the characteristics of briquettes on their calorific value

To assess the influence of the characteristics of briquettes on their calorific value, planning methods of experiment were used. Processing the results of experimental research using regression analysis allows for a complex multifactorial process to assess the variances caused by each factor separately, to determine the level of influence of the studied technological factors on the output parameters of the process [21].

An objective indicator of a quality briquette is its calorific value, which is directly related to such characteristics as density and strength.

Study the effect of various parameters of the briquetting process on the strength of briquettes. The dependence of strength on these factors can be considered as random and analysed using probabilistic methods. For effective analysis, it is necessary to identify the relationships between factors and present them in quantitative form – in the form of a mathematical model:

$$\sigma = \sigma\left(x_1, x_2, \ldots, x_n\right), \quad (1)$$

where σ is the strength of briquettes, %; x_1, x_2,…, x_n – factors influencing the result.

From physical considerations, it can be assumed that the relationship between expression (1) has the following form:

$$\sigma\left(b, x\right) = b_o + \sum_{i=1}^{n} b_i x, \quad (2)$$

where b is a free term equal to the yield at $x=0$; b_i – the regression coefficient indicating the influence of the factor on the process.

It is necessary to obtain not only the form of this dependence, based on the experimental data, but also to evaluate the influence of each factor on the strength value.

Based on the analysis of the assessment of the influence of various factors on the strength value, choose as the experimental factors: x_1 – pressing pressure, MPa; x_2 – pressing temperature, °C; x_3 – pressing time, s; x_4 – the size of the fraction supplied for pressing, mm; x_5 – the ratio of the components in the briquetting mass, %/%.

A similar relationship (2) between the factors must be identified for the calorific value. In this case, choose as experimental factors: x_1 – ash content, %; x_2 – density, kg/m^3; x_3 – the ratio of the components in the briquetting mass, %/%; x_4 – moisture, %.

Based on the order of estimation of the coefficients when using the prepared experiment plans, it is possible to obtain the experiment design matrix and determine the regression coefficients. At each experimental point will be performed two experiments. To calculate the estimates of the coefficients, the arithmetic mean of these observations will be used for each point $\widetilde{y^i} = \left(\bar{\sigma}^{i1} + \bar{\sigma}^{i2}\right)/2$. Further, based on the experimental data, calculate the estimates of the coefficients and obtain the form of the interpolation formula. The last step is to assess the significance of the regression coefficients and check the adequacy of the model. Thus, find an interpolation formula with which it would be possible to describe the dependence of the strength and calorific value of the obtained briquettes on the listed factors.

3. Results

3. 1. Characteristics of fuel briquettes

In the course of the research, the main mechanical-and-physical and thermophysical characteristics of fuel briquettes were obtained, which are presented in **Tables 1–3** and **Fig. 4–10**. The tables contain average values based on the results of 3–5 experiments.

Table 1

Characteristics of leaf fuel briquettes and their mixture with waste paper

Ratio of leaves:waste paper [%:%]	Moisture [%]	Ash content [%]	Density [kg/m^3]	Strength [%]	Volatile matter [%]	Calorific value [kJ/kg]
40:60	6.29	2.90	1074.13	100.00	20.01	19048
50:50	6.66	3.30	1050.02	100.00	20.38	19016
60:40	6.54	3.30	1048.14	100.00	21.12	18947
90:10	6.93	3.50	1040.03	100.00	21.40	18899
100:0	6.95	3.60	1036.21	93.00	21.62	18857

Table 2

Characteristics of fuel briquettes from agricultural waste

Briquette type (composition)	Moisture [%]	Ash content [%]	Density [kg/m3]	Strength [%]	Volatile matter [%]	Calorific value [kJ/kg]
Sunflower husk	3.90	2.05	1038.05	90.00	16.14	17783
Sunflower husk + starch (2:1)	6.50	3.20	988.30	93.00	13.50	17330
Buckwheat husk + cellulose (2:1)	6.40	3.2	979.91	95.00	13.60	15290

Table 3

Characteristics of bio-coal briquettes from foliage and coal

Leaves:coal ratio [%:%]	Moisture [%]	Ash content [%]	Density [kg/m^3]	Strength [%]	Volatile matter [%]	Calorific value [kJ/kg]
50:50	8.00	14.0	1172.63	91.10	17.00	18119
60:40	8.00	14.0	1121.65	93.70	17.00	18266
70:30	8.00	12.0	1070.66	96.20	12.00	18414
80:20	7.00	12.0	1020.68	97.90	12.00	18517
90:10	6.00	10.0	1009.50	98.10	9.00	18709

The mechanical strength of briquettes from leaves and waste paper in any ratio has the highest rate (100 %) in comparison with a purely deciduous sample (93 %). The density of briquettes decreases along with a decrease in cellulose content. At the same time, the calorific value of briquettes also decreases, but it has a rather high average value (18853.4 kJ/kg). Moisture and ash content are within the standard permissible values [22].

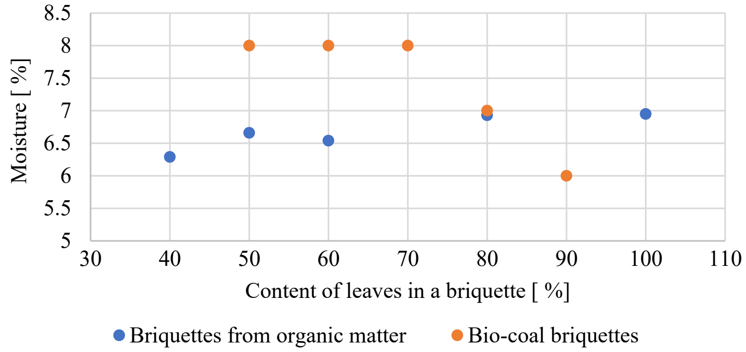

Fig. 4. Moisture content in the studied briquettes

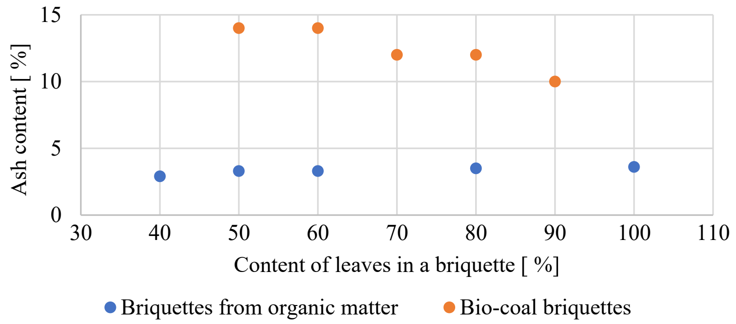

Fig. 5. Ash content of the investigated briquettes

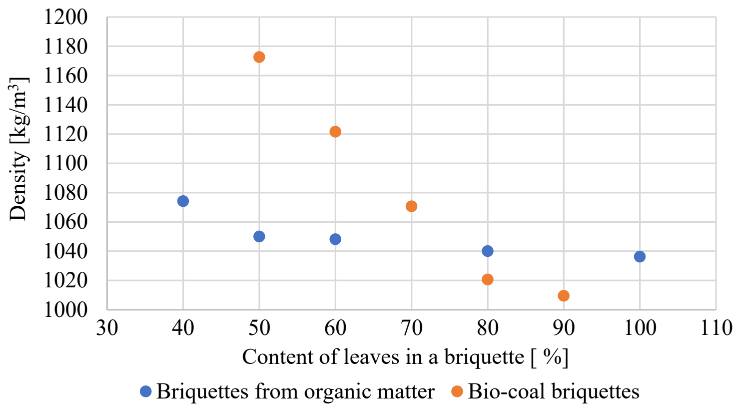

Fig. 6. Density of the investigated briquettes

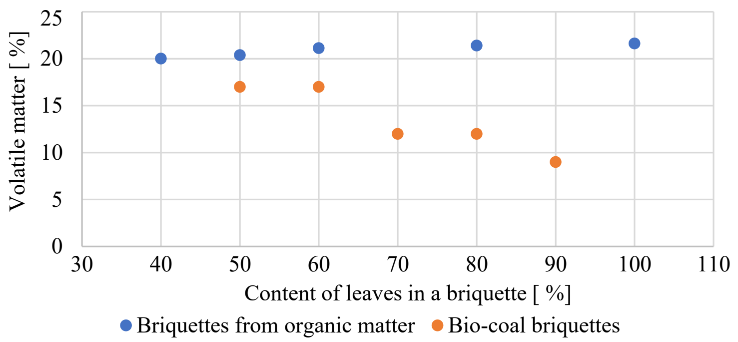

Fig. 7. Volatile matter in the investigated briquettes

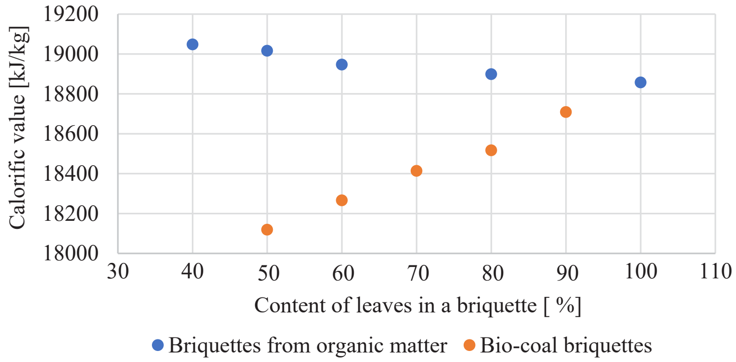

Fig. 8. Calorific value of the investigated briquettes

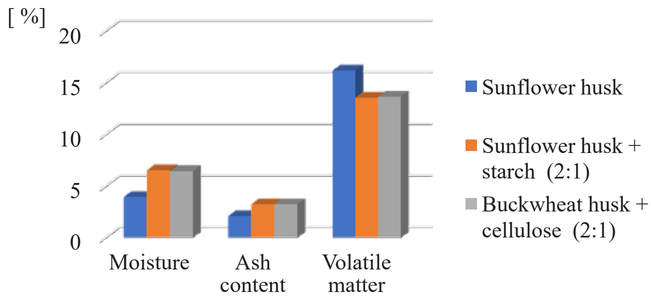

Fig. 9. The content of moisture, ash content and volatile matter in agricultural waste briquettes

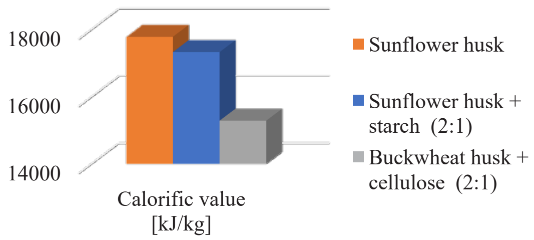

Fig. 10. Calorific value of briquettes from agricultural waste

Characteristics of briquettes from sunflower husk and buckwheat meet the relevant requirements of the standards [22]. Their calorific value is slightly lower than briquettes from leaves and waste paper. Bio-coal briquettes from foliage and coal also have characteristics that meet the requirements of the standards [22]. They have ash content, which is higher than that of briquettes from organic waste, but lower than that of Ekibastuz coal (40.9 %).

3. 2. Results of mathematical modelling

The assessment of the influence of the characteristics of briquettes on their calorific value will be considered using the example of samples from leaves and waste paper. **Table 4** shows the plan of an experiment to study the influence of various factors on the strength of briquettes and its results. The values of the process outputs were obtained as a result of experimental studies.

Based on the obtained experiment planning matrix, the regression coefficients of (2) for the manufactured fuel briquettes from organic matter were determined. The interpolation formula for the dependence of the strength of briquettes on the process parameters took the following form

$$\hat{\sigma} = 95.5 + 3.625x_1 + 0.75x_2 + x_3 + 0.05x_4 - 0.5x_5. \quad (3)$$

Table 5 gives a plan of an experiment to study the influence of various factors on the calorific value of renewable organic materials and its results. The values of the process outputs were obtained as a result of experimental studies.

Table 4
Experiment planning matrix (by strength)

Experiment number	Planning						The process output Strength σ [%]
	x_0	x_1	x_2	x_3	x_4	x_5	
1	+	+	+	+	+	+	100
2	+	–	+	+	–	–	94
3	+	+	–	+	–	–	100
4	+	–	–	+	+	+	92
5	+	+	+	–	+	–	100
6	+	–	+	–	–	+	91
7	+	+	–	–	–	+	97
8	+	–	–	–	+	–	90

Table 5
Experiment planning matrix (by the calorific value)

Experiment number	Planning					The process output Calorific value [kJ/kg]
	x_0	x_1	x_2	x_3	x_4	
1	+	+	+	+	+	18702.4
2	+	–	+	+	–	18924.3
3	+	+	–	+	–	18681.5
4	+	–	–	+	+	18694.1
5	+	+	+	–	–	18631.2
6	+	–	+	–	–	18652.2
7	+	+	–	–	–	18639.6
8	+	–	–	–	+	18631.3

Using the method of planning the experiment, the regression coefficients of equation (2) were determined and the interpolation formula for the dependence of the calorific value of briquettes on the process parameters took the following form

$$\hat{y} = 18708.40 - 30.90x_1 + 32.99x_2 + 56.06x_3 - 29.85x_4. \quad (4)$$

The obtained interpolation formulae make it possible to evaluate the influence of each of the presented parameters on the process output.

4. Discussion of experimental results

4. 1. Analysis of the main characteristics of the investigated fuel briquettes

Moisture: as known, the quality of briquettes as a fuel largely depends on their moisture content. From various sources [7, 9, 23], a conclusion can be drawn regarding the range of values of this characteristic for different organic waste (from 6 % to 10 %). The moisture content of the samples studied by us lies in the range from 3.86 to 8 %, which does not contradict the results of similar studies of scientists.

Ash content: in accordance with European quality standards for fuel pellets (DIN plus, EN plus-A2, EN-B), the ash content of fuel briquettes should be in the range of 0.5–3 % [22]. The resulting ash content of briquettes from leaves, sunflower husks and buckwheat husks varies in the range from 2.05 % to 3.6 %, which meet the requirements. The ash content of the combined briquettes of foliage and coal dust varies from 10 % to 14 % depending on the composition (**Table 1**). This exceeds the specified limits for fuel pellets, but still significantly less than ash content of the Ekibastuz coal itself, which is 36.9–40.9 % [24].

Density: the main factor that determines the mechanical strength, water resistance and caloric content of the briquette is its density. The denser the briquette, the higher its quality indicators. The lower the density of the briquettes, the lower their caloric content. For example, for a briquette density of 650–750 kg/m^3, the caloric value of briquettes is 12–14 MJ/kg; for a density of 1200–1300 kg/m^3 – 25–31 MJ/kg [25].

The investigated briquettes showed average density values from 979.91 to 1 172.63 kg/m^3, which fully meets the relevant requirements of European standards DIN 51 731, O-Norm M 7135, DIN plus, SS 18 71 20 [22].

Strength: in accordance with the scientists' research, the values of mechanical strength of 70–75 % are selected as the rejection limits when carrying out a drum test of briquettes [26]. The drum test of the investigated samples showed a fairly high degree of strength: from 90 to 100 %.

Volatile matter: the volatile matter of investigated samples is in the range from 9 to 21.4 %, which indicates a good flammability of briquettes. For comparison: the volatile matter of Ekibastuz coal ranges from 24 to 30 % [24].

Calorific value: the most important characteristic of the obtained fuel briquettes is the calorific value. This characteristic is a comparative indicator that indirectly characterizes the economic component of their use.

The calorific value of briquettes from various organic waste varies from 8 786.4 kJ/kg for briquettes from maple leaves to 21 000 kJ/kg for briquettes from sunflower husks [9, 23]. For bio-coal briquettes, depending on the percentage ratio of the components of the mixture, the calorific value is in the range from 17 058 to 23 226 kJ/kg [7, 27].

The calorific value of the studied briquettes samples varied from 15 290 to 19 048 kJ/kg. Meanwhile, the calorific value of coal from the Ekibastuz deposit ranges from 15 870 to 17 380 kJ/kg [24], which indicates a fairly high calorific value of briquettes from the considered organic and industrial waste.

4. 2. Analysis of results of the modelling

The area of experiment planning is determined by the intervals of change of input variables. **Tables 6, 7** show the intervals of change for each of the factors for which the regression equations were obtained.

Table 6

Factor variation intervals (for strength)

Factors	x_1	x_2	x_3	x_4	x_5
Main level ($x_i = 0$)	20	25	30	1.8	70/30
Upper level ($x_i = +1$)	25	30	40	3	100/0
Lower level ($x_i = -1$)	15	20	20	0.6	40/60
Variation interval	5	5	10	1.2	30/30

Table 7

Factor variation intervals (for the calorific value)

Factors	x_1	x_2	x_3	x_4
Main level ($x_i = 0$)	3.25	1055	70/30	6.62
Upper level ($x_i = +1$)	3.60	1074	100/0	6.95
Lower level ($x_i = -1$)	2.90	1036	40/60	6.29
Variation interval	0.35	19	30/30	0.33

It should be borne in mind that the resulting regression equations are presented in a normalized form. To go back to natural form, it will be necessary to carry out the reverse transformation.

The regression analysis equation (3) in natural scale will take the form:

$$\hat{\sigma} = 75.34 + 0.73X_1 + 0.15X_2 + 0.1X_3 + 0.04X_4 - 0.02X_5. \quad (5)$$

The regression analysis equation (4) in natural scale will take the form:

$$y = 17631.52 - 88.29X_1 + 1.74X + 1.87X_3 - 90.45X_4. \quad (6)$$

As the analysis of dependence (3) shows, the pressure and the pressing time have the greatest influence on the strength of the briquette, which confirms the importance of these parameters in the briquetting process.

The analysis of dependence (4) revealed that the factor x_3 (composition, i.e., the ratio in the initial briquetting mass of leaves and paper) has the greatest influence on the value of the calorific value. To a lesser extent, but moisture, ash and density have practically the same effect on the calorific value.

The adequacy of the model and the significance of the quadratic effects in both experiments will be checked.

For a given level of significance of testing the hypothesis of adequacy $\alpha = 0.05$ in accordance with the 95 % F-distribution $F_{cr} = 5.32$. In our cases: $F_1 = 2.29$ less than $F_{cr} = 5.32$ and $F_2 = 1.00$ less than $F_{cr} = 5.32$. Thus, the performed verification of the adequacy showed that the proposed models are adequate, since the errors characterizing the accuracy of the models do not exceed the observation errors.

Checking the significance of the coefficients showed that all the coefficients of these models are significant. Hence, the regression equations (3), (4), considering this remark, will remain in the same form.

5. Conclusions

It is possible to obtain fuel briquettes from organic and industrial waste of the local industry: leaves, sunflower husks, buckwheat husks, coal dust.

The calorific value of the obtained briquettes (15 290–19 048 kJ/kg) is comparable to the calorific value of coal from the Ekibastuz deposit.

Analysis of the obtained characteristics of fuel briquettes showed that they meet the standards requirements.

The analysis of the regression dependence (3) showed that the pressure and pressing time have the greatest influence on the strength of the briquette, and the size of the fractions has the least influence. At the same time, the pressing pressure factor has a 3.625 times greater effect on strength than the pressing time. To achieve maximum density, it is necessary to increase the pressing pressure, and the step should be chosen based on the absolute value of the coefficient in front of the pressure factor, which is equal to 3.625.

As follows from the regression equation (4), the greatest influence on the calorific value is exerted by its composition, i.e. the content of leaves in the feedstock. The influence of this factor is 1.8 times stronger than the effect of other factors. To increase the calorific value, it is necessary to increase the content of leaves in the briquette and reduce the moisture and ash content. The step of movement in the direction of the gradient should be chosen based on the absolute values of the coefficients in front of these factors, which are equal to 56.06, 30.90 and 29.85, respectively.

Conflict of interest

The authors declare that there is no conflict of interest in relation to this paper, as well as the published research results, including the financial aspects of conducting the research, obtaining and using its results, as well as any non-financial personal relationships.

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