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Analysis of the Characteristics of Bio-Coal Briquettes from Agricultural and Coal Industry Waste

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Abstract: One of the options for reducing harmful emissions in the production of heat energy is the use of biomass, including in combination with industrial waste (for instance, coal and coke dust). Recent studies demonstrate that a mix of biomass and coal makes it possible to obtain a bio-coal briquette with better characteristics, which is a motivating factor in the search for alternative sources of heat energy from local agricultural waste. The aim of this research is to study the properties of bio-coal briquettes from biomass (sunflower husks and leaves) and industrial waste (coal and coke dust). The raw material was grinded and used for the production of bio-coal briquettes of 20%, 30%, 40%, 50%, 60%, and 70% of biomass. The biomass was grinded to the size of no more than 2 mm for the fine fraction and no more than 6 mm for the coarse fraction. The briquettes were made mechanically using a hydraulic press with a compression pressure of 25 MPa without the use of any binder. The characteristics of the investigated bio-coal briquettes, such as density, strength, moisture content, ash content, volatile yield, calorific value, ignition time, burning duration, and burning rate, have good enough values. The fine fraction briquettes compared to the coarse fraction briquettes have a longer burning time (about threefold longer) and a lower burning rate. For all briquettes, an increase in the composition of coal dust results in a rise in the burning time, whereas the burning rate falls. The best in terms of strength, calorific value and combustion parameters are the following briquettes: 70% sunflower husk and 30% coal dust from the Karazhyra deposit; 60% sunflower husk and 40% coal dust from the Shubarkul deposit; briquettes from 70% sunflower husk and 30% coke dust; briquettes from 80% leaves and 20% coal dust from the Karazhyra deposit; and briquettes from 70% leaves and 30% coal dust from the Shubarkul deposit. The selected briquettes are suitable as an alternative source of fuel.

Keywords: bio-coal briquettes; sunflower husks; leaves; coal dust; coke dust; physical and combustion characteristics

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1. Introduction (Problem Statement)

In the modern world, there is a steady increase in the consumption of energy resources, which is determined by the high rates of industrial development and the growth of the world population.

Climate change, which is caused by aggressive human activities, is the cause of dangerous wide-scale disturbances in nature and affects the lives of billions of people on our planet. The report of the Intergovernmental Panel on Climate Change (Sixth Assessment Report (AR6)) showed that over the next two decades the world will face the inevitable multiple climate hazards associated with global warming of 1.5 °C (2.7 °F), some of which will become irreversible. To mitigate these catastrophic changes, accelerated action is needed to reduce greenhouse gas emissions.

The solution of this issue is difficult due to the introduction of energy capacities using wind, solar, etc. This is caused by the high cost of energy produced by solar and wind stations. The most promising solution is the replacement of the energy source itself: classical organic solid or liquid fuel with biofuel.

Environment, health, and ecology issues are the main concerns associated with the operation of fossil fuels both worldwide and in Kazakhstan.

According to British Petroleum, carbon dioxide emissions in Kazakhstan have tripled over the past 70 years. During the period from 2010 to 2021, carbon dioxide emissions increased from 183.9 to 219.4 million tons per year, i.e., by 19.3% [1]. According to national and international experts, climate disasters such as drought and the shallowing of rivers will become a common occurrence in Kazakhstan. According to forecasts, pasture carrying capacity in the country will decrease by 10% by 2030, water deficit will be 50% of the need by 2040, and more than 50% of the current glacial mass will be lost by 2100.

In this context, the ambitious goal of Kazakhstan to achieve carbon neutrality by 2060 has become an important step in the fight against climate change. Currently, Kazakhstan is working on the doctrine of carbon neutral development until 2060. Among the key measures are the abandonment of new coal-fired generation projects and the gradual phase-out of coal combustion (2021–2025), the implementation of a program to plant 2 billion trees (2025), doubling the share of renewable energy sources in electricity generation (2030), one hundred percent sorting of municipal solid waste (2040), sustainable agriculture on 75% of arable land (2045), 100% electrification of personal passenger transport (2045), use of only green hydrogen and the complete elimination of coal production (2050), etc.

One of the options for reducing harmful emissions is the use of biomass, including in combination with industrial waste (for example, coal and coke dust). Biomass has great potential because it is renewable, unlike fossil fuels. Biomass in its usual form is difficult to store, transport, process, and exploit due to the following factors: high moisture content, low bulk density, and variability in feedstock sizes.

These problems can be overcome by using briquetting technology—the process of compacting waste into a homogeneous solid briquette. Co-combustion of biomass with coal will expand the use of biomass energy and improve the properties of low-grade coals [2].

Biomass, especially agricultural waste, appears to be one of the most promising energy resources for developing countries. This type of waste is available as free, local, and environmentally friendly energy sources [3]. The choice of raw materials for biomass depends on the availability of waste in each specific region of the world, and this list is quite wide: sugarcane bagasse, sisal, cassava bran, dried banana leaves, rice husks and bran, corn, sunflower husks, etc. [4–8].

Studies have shown that mixing coal and biomass will make it possible to obtain a bio-coal briquette with high physical and combustion characteristics [9]. Coal and biomass are different in elemental composition: coal includes a high carbon content and heat content, but a low volatile yield, whereas biomass has a high volatile content, but a low carbon content [10].

Many experiments have been carried out in order to study the characteristics of briquettes from various plant and coal wastes. For instance, the physical and combustion characteristics of briquettes from a mixture of peanut husks and coal were determined using starch as a binder and with the addition of $Ca(OH)_2$ as a desulfurizing agent [9]. In the course of this work, the physical–mechanical and thermal properties of the obtained briquettes were studied. The results showed that the moisture content is in the range of 2.43–6.44%, the compressive strength is in the range 7.72–10.85 N/mm^2, the ash content is in the range 24.18–29.15%, calorific value is in the range 21,714.17–25,027.18 kJ/kg, combined carbon is in the range 16.77–53.22%, ignition time is in the range 22.23–45.20 s, and burning rate is in the range 16.10–28.32 g/min. These are quite good values of the thermal properties of bio-briquettes. Briquettes made from coal and peanut husk in the ratio of 60:40 have a high compressive strength of 10.85 N/mm^2, have a high calorific value of 23,628.83 kJ/kg, ignite much faster—35.76 s, and have a burning time of 22.56 min. These results allow us to state that these bio-briquettes have significant thermal properties compared to other mixtures of briquettes.

In the paper [11], various mixtures of biomass with coal were used. Namely, the mixtures used were coconut fiber mixed with brown coal, rice straw mixed with coal, and corn cobs mixed with brown coal. In all cases starch and molasses were used as a binder. The results of the study show that the studied compositions of briquettes have a good calorific value. However, briquettes from 60% coal and 40% corn cobs showed better combustible qualities compared to other compositions. This type of briquettes has the following characteristics: ash content 20.17%, moisture content 2.5%, density 0.414 g/cm^3, volatile matter 32.50%, calorific value 124.45 kJ/kg, ignition time 29.56 s, and burning time 19.76 min.

In another work [12], briquettes were made from coal waste and bananas at various composition ratios (100:0, 90:10, 80:20, 70:30, and 60:40) using calcium hydroxide as a desulfurizing agent, and starch as a binder. The results showed that the content of moisture, volatile matter, and ash content of composite briquettes ranged from 6.74 to 9.36%, from 25.25 to 39.78%, and from 6.25 to 8.75%, respectively. The carbon content, porosity index, calorific value, ignition time, burning rate, and thermal efficiency of composite briquettes ranged from 54.16 to 76.32%, from 23.42 to 44.48%, from 31.62 to 31.43 MJ/kg, from 57.24 to 180.96 s, from 0.035 to 0.083 g/min, and from 12.73 to 15.63%, respectively. The higher calorific value and lower volatile content of combined briquettes compared to biomass briquettes make them more suitable as solid fuels.

In the paper [13], the authors mixed low-grade South Sumatra coal and palm shell charcoal to produce bio-coal briquettes in order to improve fuel properties. The results of the experiments showed that the calorific value of a bio-coal briquette is greatly influenced by the composition of the raw material and the type of binder. The highest calorific value was 6438 kcal/kg for a sample with the following composition: low-grade coal—65%, palm shell charcoal—20%, and a binder (combination of starch powder, water, and liquid caustic soda in a mass ratio of 1:1:1)—15%.

The study [14] shows an analysis of the properties of bio-coal briquettes obtained by mixing cassava stalks and coal in various ratios using starch as a binder and $Ca(OH)_2$ as a desulfurizing agent. Among the briquettes obtained in this way, a sample with a content of 40% biomass showed the best combustible qualities.

All these studies have shown that bio-coal briquettes show promising results as an alternative solid fuel with properties within the limits set by international standards. These results encourage the search for other options for combining biomass and coal as a feedstock.

However, all the listed bio-coal briquettes contained a binder in their composition. The presence of a binder in the fuel briquette improves its strength, but at the same time, increases its cost.

Across the territory of Kazakhstan, a huge amount of industrial (around 700 million tons) and agricultural (about 13 million tons) waste is generated annually, which is not properly disposed of and is placed in landfills [15]. As of 1 October 2022, the availability of oilseeds, including sunflower, was 511, 794.1 tons [16]. Sunflower is the leading oil crop in Kazakhstan. It accounts for up to 70% of the sown area occupied by oil crops and 85% of the gross harvest. Due to the great economic benefits, sunflower areas are constantly growing. Over the past 10 years, they have increased fivefold and have reached almost 1 million hectares [17]. Sunflower husk is the main waste in the processing of sunflower seeds. Sunflower husk as a fuel has good characteristics, has a low ash content, is highly flammable, and has a high calorific value. Regrettably, no information is currently available on the possibility of obtaining bio-coal briquettes and their properties obtained through mixing sunflower husks with coal or coke dust. In the current studies, the possibilities of bio-coal based on sunflower cake have been presented [18], or the burning of sunflower husks in a vortex layer was investigated [19]. However, burning husks in a vortex layer has a number of considerable drawbacks. Firstly, currently there are no industrially produced boilers and furnaces designed for burning husks. Secondly, the husk can be satisfactorily burned in flare-layered and shaft-type furnaces only, with a low forcing of the combustion process. This combustion option is suitable only for low power boilers or with a 1.5–3-fold decrease in evaporative capacity of medium power boilers. There is a need to search for the possibility of utilizing biomass in another way, e.g., its briquetting.

Apart from the problem of disposing these biowastes, there is a problem of disposing coal and coke dust produced in mining and processing. According to experts, their volumes can be from 30 to 70% of the main volume of production and processing [20]. For example, according to the data of the petroleum coke calcination enterprise (UPNK-PV LLP (Pavlodar, Kazakhstan)), the output of coke dust as a waste is 200 tons annually. Thus, a thorough analysis of the possibility of using bio-coal briquettes from local raw materials as an alternative fuel is necessary.

2. Materials and Methods

The aim of this research is to obtain bio-coal briquettes from biomass (sunflower husks, leaves) and industrial waste (coal and coke dust) and to analyze their characteristics. The starting material for the test briquettes was waste of organic origin (leaves, sunflower husks) and industrial waste (coke and coal dust).

The preparation of the feedstock was as follows:

- cleaning from foreign inclusions (glass, plastic, metal, etc.);
- drying in the open air until air-dry state;
- grinding to a size of no more than 2 mm for a fine fraction and no more than 6 mm for a coarse fraction.

For the research, bio-coal briquettes were made from organic waste in combination with coal and coke dust in various ratios of 30:70%, 40:60%, 50:50%, 60:40%, 70:30%, and 80:20%. The following types of briquettes were made:

- sunflower husk of fine fraction (0–2 mm): coal dust from the Karazhyra deposit;
- sunflower husk of coarse fraction (3–6 mm): coal dust of the Karazhyra deposit;
- sunflower husk of fine fraction (0–2 mm): coal dust of the Shubarkul deposit;
- sunflower husk of coarse fraction (3–6 mm): coal dust of the Shubarkul deposit;
- sunflower husk of fine fraction (0–2 mm): coke dust;
- sunflower husk of coarse fraction (3–6 mm): coke dust;
- leaves of fine fraction (0–2 mm): coal dust from the Karazhyra deposit;
- leaves of fine fraction (0–2 mm): coal dust of the Shubarkul deposit.

The fuel characteristics of the industrial waste used are presented in Table 1.

Table 1. Characteristics of feedstock for bio-coal briquettes.

Name of Indicator (Average Value)	Sunflower Husk (0–2 mm)	Sunflower Husk (3–6 mm)	Leaves (0–2 mm)	Coal Dust of the Shubarkul Deposit	Coal Dust from the Karazhyra Deposit	Coke Dust LLP "UPNK-PV"
Total moisture in the working condition of the fuel, %	3.86	5.77	2–4	15.30	14.00	3.06
Ash content for dry fuel, %	2.05	2.26	6.50	12.10	18.50	6.65
The yield of volatile matter on a dry ash-free state of the fuel, %	36.21	32.74	20.75	43.40	47.00	9.81
Net calorific value, kJ/kg	19,031.00	18,900.00	21,206.91	29,315.00	26,720.00	26,871.00

To manufacture briquettes, mixed raw materials were pressed by a hydraulic press with a constant pressure of 25 MPa. The resulting briquettes were dried in the room to an air-dry state. Briquettes have a cylindrical shape with a diameter of 30 mm and the weight of 4 g.

In the course of the study, physical–mechanical characteristics (density, strength, humidity) and thermophysical characteristics (humidity, ash content, volatile matter yield, lower calorific value, burning time and speed, ignition time) of fuel briquettes were determined.

The density of briquettes was determined in accordance with [21]. For this procedure, a standard container is filled with a sample and weighed. The bulk density was calculated based on the net weight and the internal volume of the container.

The mechanical strength of the obtained samples of briquettes was determined in accordance with [22]. The test samples were subjected to controlled impacts by colliding the briquettes with each other and with the walls of a special rotating chamber. The strength was calculated by sieve analysis of changes in the particle size distribution of the drum sample [23].

The determination of the moisture content of the prepared samples was carried out according to [24]. The procedure consisted of drying the sample of briquettes in an oven at a temperature of 105 ± 2 °C for 60 min and calculating the weight loss of the taken sample.

The ash content of briquettes from organic waste and briquettes containing up to 50% industrial waste was determined in accordance with the method described in [25]. The ash content was determined by calculation, based on the mass of the residue formed after burning a sample of biofuel in a muffle furnace with free air access and a temperature of (550 ± 10) °C. For bio-coal briquettes with industrial waste content of more than 50%, the combustion of a sample of fuel and the calcination of the ash residue to constant weight was carried out at a temperature of (815 ± 10) °C. After cooling and weighing, the change in weight was determined.

The yield of volatile matter was determined according to [26]. A weighed portion of the analytical sample was heated without air in a muffle furnace at a temperature of (900 ± 10) °C for 7 min. The yield of volatile matter was determined as the weight loss of the fuel sample minus the weight loss due to the moisture content in the sample.

The determination of the lower calorific value of the briquettes was carried out according to [27]. The essence of the method for determining the calorific value was the complete combustion of a sample of the fuel mass in a calorimetric bomb. The process took place in an isothermal mode at a constant volume in a compressed oxygen medium at a pressure of 29.4·105 Pa. The researchers measured the temperature of the water in the calorimeter vessel and made 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.

The following combustion characteristics of bio-coal briquettes were measured:

- burning time;
- ignition time;
- weight of the briquette.

Based on the obtained data, the burning rate of bio-coal briquettes was calculated.

Burning time measurements were made similarly to the measurements made in [28,29] by burning bio-coal briquettes placed on a perforated sheet in the open air in a gas burner flame.

The change in the mass of the briquette was monitored every 10 s throughout the entire combustion process. The end of the burning time was considered the moment when the mass of the briquette stopped changing.

The ignition time is characterized by the time from the start of the test to the onset of stable flame combustion, which is visually recorded. To perform this, a burner flame is brought to the fuel briquette and the ignition time is recorded using a stopwatch.

The mass of the briquette was measured on a scale and was subsequently used to determine the burning rate of bio-coal briquettes according to the following formula:

$$B = \frac{m_1 - m_2}{T}$$

where B—burning rate, g/s;

m_1—initial mass of fuel before combustion, g;

m_2—final mass of ash after combustion, g;

T—total burning time, s.

3. Results and Discussion

The object of research is the characteristics of briquettes, including the characteristics of combustion.

Table 2 presents the results of the analysis of briquettes from sunflower husks and coal dust from the Karazhyra deposit.

Table 2. The results of the analysis of briquettes (sunflower husk and Karazhyra coal dust).

No.	Briquette Composition SH/CD1, %	Particle Size	Density (kg/m^3)	Strength (%)	Moisture (%)	Ash (%)	Volatile Matter, (%)	Calorific Value, (kJ/kg)
	SNI	-	-	-	≤8%	≤8%	≤15%	≥20,950
1	80/20	0–2	869.26	83.84	4.00	5.04	38.07	21,166.83
2	70/30	0–2	901.48	80.95	4.60	6.09	38.75	21,337.71
3	60/40	0–2	958.62	75.31	5.00	8.03	40.26	22,106.61
4	50/50	0–2	1000.91	69.27	6.50	9.88	40.85	23,045.00
5	40/60	0–2	1047.98	66.46	7.20	10.42	41.96	23,644.40
6	30/70	0–2	1079.54	64.09	7.50	11.87	42.18	24,675.23
7	80/20	3–6	865.97	71.13	4.50	5.31	34.80	20,464.00
8	70/30	3–6	872.25	71.07	5.00	6.83	36.60	20,989.36
9	60/40	3–6	903.93	68.49	5.60	8.86	37.56	22,028.00
10	50/50	3–6	932.14	66.24	6.00	10.38	38.98	22,810.00
11	40/60	3–6	947.34	63.58	6.50	11.70	40.12	23,292.37
12	30/70	3–6	966.54	61.38	7.20	12.63	41.67	24,374.00

SH = Sunflower husk, CD1 = Coal dust (Karazhyra).

Table 2 shows that the moisture content of the obtained samples does not exceed 7.5%, the ash content lies in the range from 5.04 to 12.63%, the calorific value ranges from 20,464.0 kJ/kg to 24,413.3 kJ/kg, and volatile matter are in the range from 38.07% to 42.18%. The high yield of volatile matter negatively affects the duration of combustion and is associated with the specifics of the plant materials used.

Table 3 presents the results on the burning rate, burning time, and ignition of briquettes from sunflower husks and coal dust from the Karazhyra deposit.

The results showed that the briquettes of this composition showed good values in terms of combustion characteristics. The Indonesian National Standard (SNI) was used for the comparison since there is no national standard for briquettes in the Republic of Kazakhstan.

The composition of the bio-coal briquette and the particle size of the mixture affect the main characteristics of the fuel briquette. A finer fraction (0–2 mm) leads to better characteristics in terms of strength, ash content, calorific value, and burning time in the absence of a binder in the briquette. Briquettes of a fine fraction compared to briquettes of a coarse fraction have a longer burning time (about three times longer) and a lower burning rate. For all briquettes, with an increase in the composition of coal dust, the burning time increases, and the burning rate decreases. This can be explained as when briquettes burn with a finer fraction, the effect of compacting their structure can be seen. Consequently, the denser briquettes burn longer at a lower burning rate. The content increase in the coal fraction in the briquette leads to decline of a volatile yield (Tables 3 and 4). As ignition conditions deteriorate, the burning rate decreases and increases the total time of the briquette burning. The ignition time of these briquettes is small (within 23 s). It should be noted that the shorter the ignition period, the better the combustion process of the fuel briquette will be.

Table 3. The results of burning rate, burning time, and ignition (sunflower husk and Karazhyra coal dust).

No.	Briquette Composition SH/CD1 (%)	Particle Size (mm)	Burning Rate (g/s)	Burning Time (min)	Ignition Time (s)
1	80/20	0–2	0.00196	34.00	16
2	70/30	0–2	0.00115	58.13	16
3	60/40	0–2	0.00074	90.00	16
4	50/50	0–2	0.00073	91.67	16
5	40/60	0–2	0.00072	93.11	18
6	30/70	0–2	0.00071	93.40	20
7	80/20	3–6	0.00551	12.09	8
8	70/30	3–6	0.00434	15.36	10
9	60/40	3–6	0.00386	17.28	12
10	50/50	3–6	0.00320	20.85	18
11	40/60	3–6	0.00198	33.68	20
12	30/70	3–6	0.00124	53.78	23

Table 4. The results of the analysis of briquettes (sunflower husk and Shubarkul coal dust).

No.	Briquette Composition SH/CD1, %	Particle Size	Density (kg/m^3)	Strength (%)	Moisture (%)	Ash (%)	Volatile Matter, (%)	Calorific Value, (kJ/kg)
	SNI	-	-	-	≤8%	≤8%	≤15%	≥20,950
1	80/20	0–2	895.28	73.14	5.50	3.86	37.11	21,087.81
2	70/30	0–2	918.70	72.18	5.95	4.77	37.81	21,878.25
3	60/40	0–2	1033.57	71.54	6.42	5.27	38.02	23,144.61
4	50/50	0–2	1040.19	70.63	6.53	6.58	38.67	23,799.24
5	40/60	0–2	1053.40	67.39	6.90	7.22	39.00	25,201.40
6	30/70	0–2	1070.46	65.28	7.50	8.79	39.60	26,005.54
7	80/20	3–6	885.09	68.25	5.00	4.23	33.56	20,983.00
8	70/30	3–6	905.39	67.02	5.22	5.21	34.88	21,675.98
9	60/40	3–6	936.13	66.27	5.47	6.5	36.01	23,007.12
10	50/50	3–6	993.58	65.86	5.50	7.18	36.70	23,452.10
11	40/60	3–6	972.35	64.72	5.97	8.16	37.65	24,796.38
12	30/70	3–6	1022.51	62.29	6.50	9.15	38.20	25,814.68

SH = Sunflower husk, CD2 = Coal dust (Shubarkul).

The most optimal ratio was the ratio of a mixture of 70% sunflower husk and 30% coal dust with the following characteristics: humidity 4.6%, ash content 6.09%, volatile matter 38.75%, and calorific value 21,337.71 kJ/kg.

Table 4 presents the results of the analysis of briquettes from sunflower husks and coal dust from the Shubarkul deposit.

Table 5 presents the results on the burning rate, burning time, and ignition of briquettes from sunflower husks and coal dust from the Shubarkul deposit.

Table 5. The result of burning rate, burning time and ignition (sunflower husk and Shubarkul coal dust).

No.	Briquette Composition SH/CD1 (%)	Particle Size (mm)	Burning Rate (g/s)	Burning Time (min)	Ignition Time (s)
1	80/20	0–2	0.00114	58.27	14
2	70/30	0–2	0.00082	81.78	15
3	60/40	0–2	0.00076	88.12	18
4	50/50	0–2	0.00070	95.87	18
5	40/60	0–2	0.00061	108.60	20
6	30/70	0–2	0.00058	115.38	20
7	80/20	3–6	0.00551	76.25	12
8	70/30	3–6	0.00482	77.50	14
9	60/40	3–6	0.00434	79.26	14
10	50/50	3–6	0.00386	81.48	15
11	40/60	3–6	0.00320	85.90	18
12	30/70	3–6	0.00198	98.57	22

In this case, as in the previous version, a finer fraction of the mixture (0–2 mm) gives better characteristics in terms of strength, calorific value, and combustion parameters.

The results of the analysis show that these briquettes have good performance in terms of moisture content, ash content, calorific value, and combustion parameters. It should be noted that the ash content is lower than in the previous case and meets the requirements for bio-coal briquettes. Briquettes from 60% sunflower husk and 40% coal dust from the Shubarkul deposit showed the best characteristics compared to other compositions of this type of briquettes.

Tables 6 and 7 present the results of the analysis of briquettes from sunflower husks and coke dust.

Table 6. The results of the analysis of briquettes (sunflower husk and coke dust).

No.	Briquette Composition SH/CD1, %	Particle Size	Density (kg/m^3)	Strength (%)	Moisture (%)	Ash (%)	Volatile Matter, (%)	Calorific Value, (kJ/kg)
	SNI	-	-	-	≤8%	≤8%	≤15%	≥20,950
1	80/20	0–2	995.85	86.10	5.24	2.98	30.17	20,449.46
2	70/30	0–2	1061.57	84.15	5.12	3.45	28.52	20,849.99
3	60/40	0–2	1065.38	78.20	4.70	4.01	25.33	21,867.93
4	50/50	0–2	1123.25	71.34	4.52	4.28	23.25	22,577.16
5	40/60	0–2	1169.96	68.16	4.17	4.64	20.15	23,086.95
6	30/70	0–2	1225.27	66.59	4.09	5.11	18.65	23,995.62
7	80/20	3–6	856.78	85.30	3.87	3.35	27.84	20,344.66
8	70/30	3–6	860.31	83.45	3.63	3.59	25.64	20,685.23
9	60/40	3–6	897.38	74.60	3.56	4.24	23.57	21,589.36
10	50/50	3–6	1054.33	63.61	3.38	4.78	21.76	22,406.21
11	40/60	3–6	1164.91	57.32	3.29	4.92	18.75	22,899.74
12	30/70	3–6	1207.84	56.28	3.23	5.64	16.69	23,708.99

SH = Sunflower husk, CD = Coke dust.

Table 7. The result of burning rate, burning rime and ignition (sunflower husk and coke dust).

No.	Briquette Composition SH/CD1 (%)	Particle Size (mm)	Burning Rate (g/s)	Burning Time (min)	Ignition Time (s)
1	80/20	0–2	0.001107	60.20	18
2	70/30	0–2	0.001040	64.11	19
3	60/40	0–2	0.000880	75.78	20
4	50/50	0–2	0.000800	83.33	22
5	40/60	0–2	0.000752	88.68	22
6	30/70	0–2	0.000690	96.67	24
7	80/20	3–6	0.001699	39.23	12
8	70/30	3–6	0.001358	49.09	14
9	60/40	3–6	0.000950	70.17	15
10	50/50	3–6	0.000900	74.07	16
11	40/60	3–6	0.000859	77.64	18
12	30/70	3–6	0.000800	83.33	22

Moisture content of briquettes from sunflower husk and coke dust does not exceed 5.24%, ash content is in the range of 5.64%, volatile matter is in the range from 16.69% to 30.17%, and the calorific value is in the range from 20,344.66 kJ/kg to 23,995.62 kJ/kg. The results showed that in this case too, a finer fraction of the mixture (0–2 mm) gives better characteristics in terms of strength, calorific value, and burning time. Briquettes from 70% sunflower husk and 30% coke dust with an ash content of 3.45%, moisture content 5.12%, density 1061.57 kg/m^3, volatile matter yield 28.52%, calorific value 20,849.99 kJ/kg, time ignition 19 s, and burning time 64.11 min showed good combustible and strength qualities compared to other compositions of this type of briquettes.

Tables 8 and 9 present the results of the analysis of briquettes from leaves and coal dust from the Karazhyra deposit.

Table 8. The results of the analysis of briquettes (leaves and Karazhyra coal dust).

No.	Briquette Composition SH/CD1, %	Particle Size	Density (kg/m^3)	Strength (%)	Moisture (%)	Ash (%)	Volatile Matter, (%)	Calorific Value, (kJ/kg)
	SNI	-	-	-	≤8%	≤8%	≤15%	≥20,950
1	80/20	0–2	1116.95	97.24	4.50	8.33	25.46	23,241.79
2	70/30	0–2	1151.12	96.45	5.50	9.32	28.07	23,478.12
3	60/40	0–2	1170.16	95.26	6.00	11.00	30.80	24,111.34
4	50/50	0–2	1177.92	94.78	7.00	12.01	32.68	24,546.12
5	40/60	0–2	1222.60	93.61	7.40	13.11	35.80	24,704.58
6	30/70	0–2	1224.96	92.56	8.50	14.42	37.50	25,415.67

L = Leaves, CD1 = Coal dust (Karazhyra).

The results of the analysis of briquettes from leaves and coal dust of the Karazhyra deposit showed that the main characteristics of these briquettes basically correspond to the criteria for biofuel briquettes. The humidity of the obtained briquettes does not exceed 8.5%, volatile matter are in the range from 25.46% to 37.50%, the calorific value is in the range from 23,241.79 kJ/kg to 25,415.67 kJ/kg. These values are good indicators of biofuel briquettes. It should be noted that the ash content of these briquettes ranges from 8.33% to 14.42%, which is slightly higher than the requirements of the standard, but much lower than the ash content of coal currently used in small boilers and in private households. The burning time of briquettes from leaves significantly exceeds the corresponding indicators of briquettes from sunflower husks. The increase in burning time is associated with a higher content of lignin in the leaves and a higher density of the briquette.

Table 9. The result of burning rate, burning time and ignition (leaves and Karazhyra coal dust).

No.	Briquette Composition SH/CD1 (%)	Particle Size (mm)	Burning Rate (g/s)	Burning Time (min)	Ignition Time (s)
1	80/20	0–2	0.00066	101.50	20
2	70/30	0–2	0.00064	104.00	16
3	60/40	0–2	0.00061	109.23	16
4	50/50	0–2	0.00056	120.00	18
5	40/60	0–2	0.00044	152.13	20
6	30/70	0–2	0.00043	154.33	16

Briquettes of a composition of 80% leaves and 20% coal dust with an ash content of 8.30%, humidity 4.50%, density 1116.95 kg/m^3, volatile matter yield 25.46%, calorific value 23,241.79 kJ/kg, time ignition 20 s, and burning time 101.50 min showed the best combustible and strength properties compared to other compositions of this type of briquettes.

Tables 10 and 11 present the results of the analysis of briquettes from leaves and coal dust from the Shubarkul deposit.

Table 10. The results of the analysis of briquettes (leaves and Shubarkul coal dust).

No.	Briquette Composition SH/CD1, %	Particle Size	Density (kg/m^3)	Strength (%)	Moisture (%)	Ash (%)	Volatile Matter, (%)	Calorific Value, (kJ/kg)
	SNI	-	-	-	≤8%	≤8%	≤15%	≥20,950
1	80/20	0–2	1272.60	98.64	4.50	7.42	24.58	21,863.27
2	70/30	0–2	1280.34	97.35	4.68	8.02	26.31	22,905.68
3	60/40	0–2	1297.05	96.43	5.00	8.24	29.00	23,498.19
4	50/50	0–2	1339.65	95.81	5.60	9.30	30.68	24,657.70
5	40/60	0–2	1348.57	94.69	6.00	9.86	32.70	25,807.69
6	30/70	0–2	1358.16	93.95	6.40	10.40	34.60	26,520.60

L = Leaves, CD2 = Coal dust (Shubarkul).

Table 11. The result of burning rate, burning time, and ignition (leaves and Shubarkul coal dust).

No.	Briquette Composition SH/CD1 (%)	Particle Size (mm)	Burning Rate (g/s)	Burning Time (min)	Ignition Time (s)
1	80/20	0–2	0.00097	68.48	16
2	70/30	0–2	0.00091	73.23	16
3	60/40	0–2	0.00081	81.91	18
4	50/50	0–2	0.00076	87.78	18
5	40/60	0–2	0.00052	128.65	18
6	30/70	0–2	0.00038	175.00	18

The results of the analysis showed that the main characteristics of these briquettes also meet the criteria for biofuel briquettes. The moisture content of the obtained briquettes does not exceed 6.4%, the ash content ranges from 7.42% to 10.40%, volatile matter ranges from 24.58% to 34.60%, and the calorific value ranges from 21,863.27 kJ/kg up to 26,520.60 kJ/kg. Briquettes from 70% leaves and 30% coal dust with an ash content of 8.02%, moisture content 4.68%, density 1280.34 kg/m^3, volatile matter output 26.31%, calorific value 22,905.68 kJ/kg, ignition time 16 s, and burning time 73.23 min showed good combustible and strength properties in comparison with other compositions of this type of briquettes. The ash content in this case is somewhat higher than the standardized values, but much less than the ash content of coal, which makes briquettes of this composition less environmentally harmful.

It should be noted that the strength of briquettes is one of the essential characteristics of this type of fuel. In the studied bio-coal briquettes, the strength is largely determined by the composition (the ratio between the components of the mixture).

Figure 1 shows that with an increase in the content of coal or coke dust in the briquette, the strength decreases. Moreover, for briquettes from sunflower husks and coarse coke dust, the decrease in strength is the most significant compared to other mixtures. Briquettes from leaves and coal dust showed the highest strength in the entire range of ratios. This is due to the high content of natural binder (lignin) in the leaves. In the remaining briquettes, the absence of a binder affected the strength of the final product. However, for some ratios of husks and coal dust, or coke dust, the strength values are quite high (70–85%).

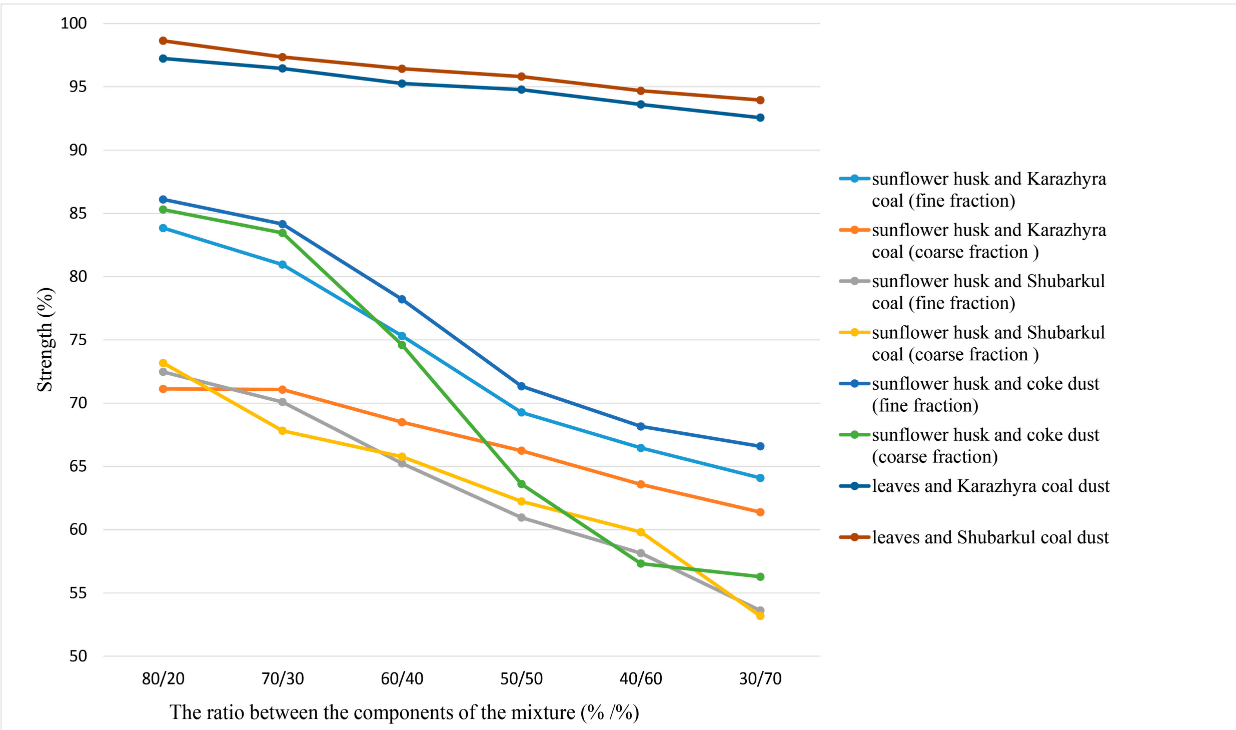

Figure 1. The dependence of the strength of the briquette on the ratio between the components of the mixture.

It is known that the ash content of a bio-coal briquette determines its environmental efficiency. Therefore, this indicator was analyzed with a change in the type and ratio of the components of the bio-coal mass (Figure 2).

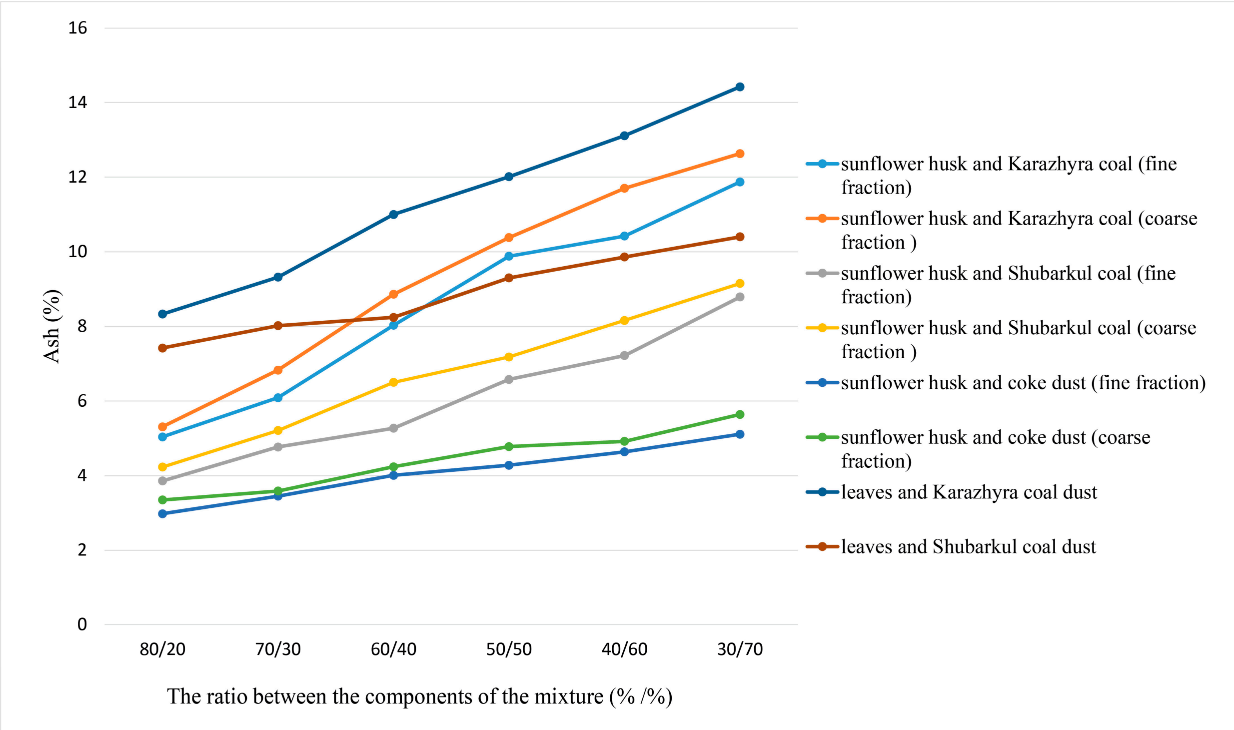

Figure 2. Change in ash content depending on the type and ratio of the components of the bio-coal mass.

The nature of the change in the ash content of the briquette is the same for different types and compositions of bio-coal raw materials: with a decrease in the biomass content, the ash content will increase. The reason is the different initial ash content of the mixture components.

Figure 3 shows the nature of the change in the moisture content of the obtained bio-coal briquettes. It can be argued that for briquettes from sunflower husks, leaves, and coal dust, the moisture content increases with the increase in the content of coal dust in the mixture. For briquettes from husks and coke dust, this characteristic behaves differently: with an increase in the content of coke dust, the humidity decreases. This is due to the lower moisture content in coke dust than in coal.

The most important characteristic of any briquette as a fuel is its calorific value. Taking this into account, the change in heat generation during the combustion of briquettes was studied depending on the type and ratio of components (Figure 4). The calorific value of all studied bio-coal briquettes showed good values (from 20,449.46 to 26,520.60 kJ/kg). The briquettes from leaves and coal showed the best value. Even the minimum content of coal and coke dust (20%) gives a good result in terms of calorific value.

The obtained values showed that the studied bio-coal briquettes have good thermal properties. Therefore, they can be used as a source of heat generation at a local level, thereby reducing dependence on coal as a source of heat generation. The briquetting process is viable for converting biowaste into fuel for small scale energy and domestic use in an affordable and efficient manner. This process is economical, cheap, environmentally friendly, and affordable, and it can be used by housing and communal services, farms, as well as rural residents in various regions of the country.

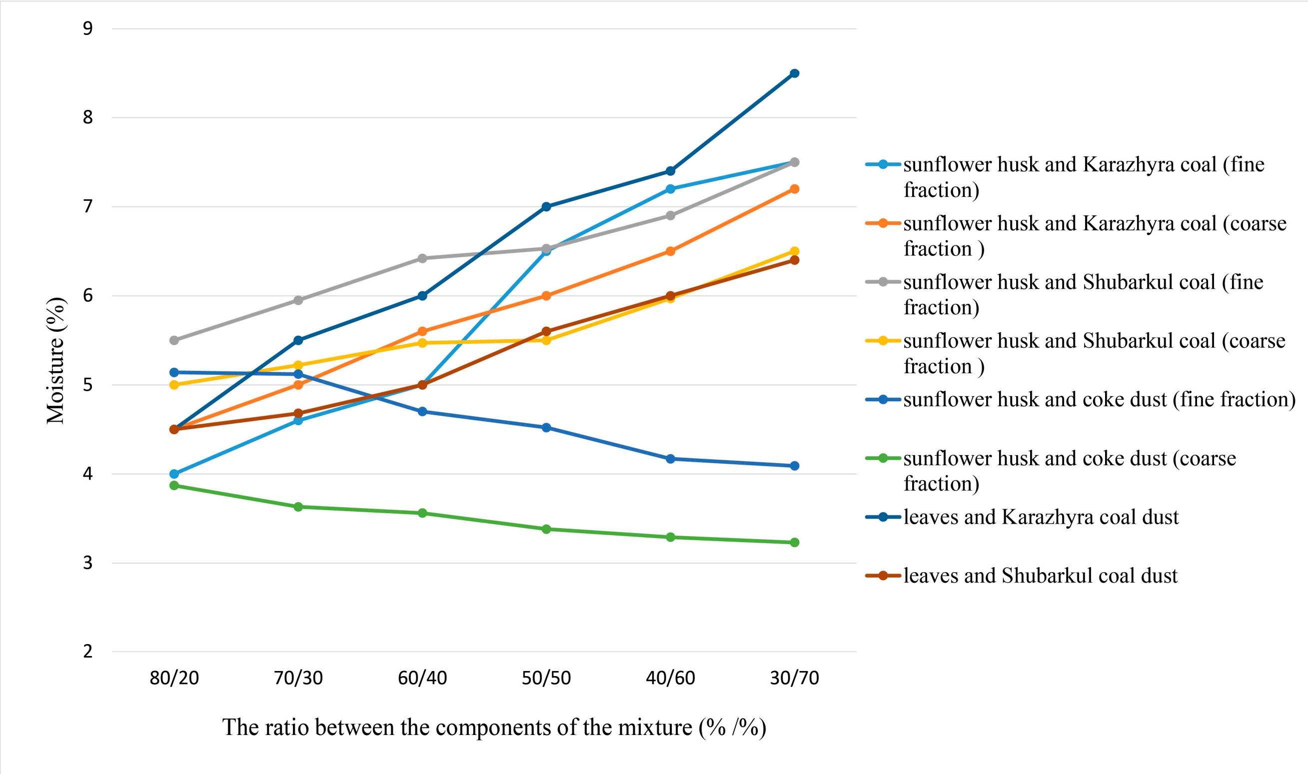

Figure 3. The dependence of the moisture content of briquettes on the type and ratio of the components of the bio-coal mass.

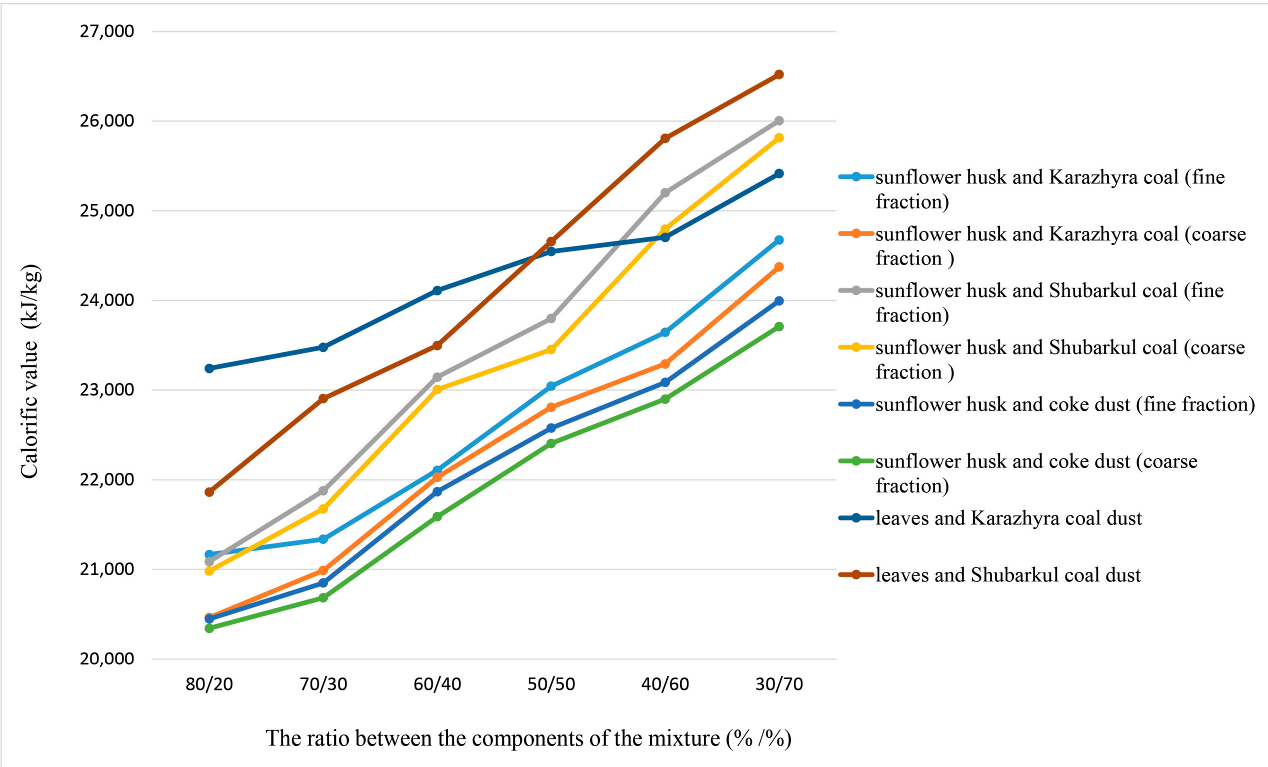

Figure 4. Change in the calorific value of briquettes depending on the type and ratio of the components of the mixture.

The required pressing pressure in the production of the developed fuel briquettes without a binder is at least 25 MPa. According to the technical characteristics of briquetting presses manufactured by Gemco Energy, ABC Machinery and others, the average cost of electrical energy for briquetting is from 45 to 60 kWh per 1 ton of briquettes [30–32].

The sufficient strength of the developed briquettes allows them to be produced in a briquetting press without any heating. The absence of energy costs for heating in the briquette press allows for a reduction in electric power consumption by 25–30%. Considering the low price of electricity in the Republic of Kazakhstan, such as USD 0.12 per kilowatt-hour in the city of Pavlodar [33], the production of fuel briquettes is feasible in terms of electricity expenses.

It should also be noted that the characteristics of bio-coal briquettes containing leaves significantly depend on the characteristics of the raw material (leaves): place, time, method of collection, etc.

4. Conclusions and Future Research Direction

In this work, the authors analyzed bio-coal briquettes from biomass and industrial waste. The study offered a solution to the problem associated with disposal of sunflower waste and leaf litter. Local raw materials (sunflower husks and leaves) in combination with coal and coke dust are suitable as an alternative source of fuel. Characteristics of the investigated bio-coal briquettes, such as density, strength, moisture content, ash content, volatile yield, calorific value, ignition time, ignition duration, and burning rate have quite good values. The characteristics of the studied briquettes demonstrated that the best in terms of strength, calorific value and combustion parameters are 70% of sunflower husk and 30% of coal dust from the Karazhyra deposit; 60% of sunflower husk and 40% of coal dust from the Shubarkul deposit; briquettes from 70% of sunflower husk and 30% of coke dust; briquettes from 80% of leaves and 20% of coal dust from the Karazhyra deposit; and briquettes from 70% of leaves and 30% of coal dust from the Shubarkul deposit. Briquettes from a fine fraction compared to briquettes from a coarse fraction have a threefold longer burning time and a lower burning rate. For all briquettes, with an increase in the composition of coal dust, the burning time increases, and the burning rate decreases. The resulting briquettes ignite faster, emit a sufficient amount of heat with a significant calorific value, are denser, and more durable. Briquetting technology has great potential for converting biowaste into fuel for use in an affordable and efficient manner. This process is economical, environmentally friendly, cheap and therefore affordable, and can be used by small boiler houses, housing and municipal services, farms, and residents in rural areas. The absence of a binder in the composition of the briquettes decreases the cost of bio-coal briquettes. Bio-coal briquettes can be used as a source of fuel on a local level, thus reducing dependence on coal as a source of heat generation.

The obtained results make a possibility to continue research in this direction. Future research will focus on the efficiency of using bio-coal briquettes from sunflower husks, leaves mixed with coal and coke dust in small boilers. The authors plan to study the issues of economic analysis of the use of these bio-coal briquettes as fuel, as well as to investigate the environmental aspects of burning these briquettes.

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