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THERMAL CHARACTERISTICS OF BRIQUETTES FROM INDUSTRIAL AND PLANT WASTE

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The monograph discusses the methodology and results of experimental studies to determine the thermal characteristics of combined fuel briquettes. The purpose of the scientific work is to acquire deeper knowledge and skills by undergraduates in the disciplines «Scientific and technical problems of heat power engineering and heating engineering», «Theory and technology of thermotechnical experiment» and «Use of secondary energy resources». For doctoral students, the monograph will be useful in mastering the discipline «Methods of Scientific Research» and «Modeling and optimization of Heat power processes». Recommended for teachers, students, master's and doctoral students of the educational program «Heat Power Engineering».

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Introduction

The rapidly growing pace of infrastructure development encourages greater consumption of fossil energy resources, which are non-renewable and have a fairly serious negative impact on the environment when used. Therefore, at the moment there is an urgent question about the study, implementation and implementation of technologies that make it possible to use waste that has energy potential.

The agro-industrial and industrial complex has a large amount of secondary raw materials. The use of this waste is not carried out due to the low development of technology. Many types of plant and industrial waste can be used as an energy source. Biomass is one of the alternative sources of heat; its advantage is its availability and renewability.

The proposed technology for recycling these resources is briquetting. But, due to little knowledge of the properties and characteristics of biomass and industrial waste, the technology has not received proper implementation and distribution in the CIS.

Studying the properties of various plant and industrial wastes, studying their characteristics during the combustion process, and analyzing the conditions for briquetting will allow us to analyze the possibility of creating energy-efficient fuel briquettes. At the same time, the amount of industrial waste, tons of which are thrown away and cannot be recycled, will be significantly reduced. The use of plant waste will reduce the amount of harmful emissions that are generated when burning traditional energy sources.

In the modern world, high rates of infrastructure development lead to a significant increase in energy consumption, which leads to the depletion of energy resources and has a detrimental effect on the environment.

In connection with this fact, the development and implementation of production technology and the use of alternative energy sources by processing secondary raw materials is a pressing issue.

Agricultural (plant) and industrial wastes, which are generated in fairly large quantities, act as secondary raw materials. An urgent issue is to determine the thermal characteristics of fuel briquettes from plant and industrial waste in order to justify their energy use.

The objectives of this work are to determine the thermal characteristics of briquettes from various agricultural (plant) and industrial wastes, conduct a comparative analysis to identify the most effective samples, as well as study the influence of the fractional composition of fuel briquettes on the calorific value.

The practical significance of the work lies in the possible use of the obtained thermal characteristics of briquettes for further scientific research. The study will allow us to evaluate the energy efficiency and feasibility of using briquettes as an alternative source of heat. The experimental work carried out to study briquettes made from industrial and plant waste will make it possible to determine the optimal ratios of raw materials in the mixture for their further use as fuel.

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1 Plant and industrial waste as sources of raw materials for the production of fuel briquettes

1.1 The relevance of using plant and industrial waste as fuel raw materials

In the modern world, the increasing pace of infrastructure development, the increase in the world population, the deviation of the climatic background from norms, the ecological state of the planet and the emerging shortage of traditional energy sources poses an acute question for society about the creation, implementation and use of alternative energy sources.

World consumption of traditional energy sources is increasing every year. According to the British Petroleum review of the global energy market for 2019, a ranking of the leading countries in coal fuel production has been compiled. According to this review, the leading position in the production of coal fuel is occupied by China – 3683.0 million tons, Russia ranks sixth – 441.3 million tons, Kazakhstan is in tenth place – 117.8 million tons [1].

In the ranking of countries for natural gas production, according to an analysis conducted by British Petroleum for 2020, the United States takes the leading position – 914.6 billion m^3/year, Russia occupies the second position – 638.5 billion m^3/year, Kazakhstan is in 22nd place – 31.7 billion m^3/year. The total global consumption of natural gas is 3853.7 billion m^3/year [2].

In the ranking of countries for oil production according to British Petroleum data for 2020, the leading position is occupied by the United States – 712.7 million tons, Russia is in second position – 524.5 million tons, Kazakhstan is in 14th place – 86.1 million tons in year. Total oil production in the world is 4165.1 million tons [3].

An important issue is the state of the environment and climate change. Consumption of fossil fuels causes serious environmental damage. In the process of burning fossil fuels, carbon dioxide (about 35 billion tons per year) and methane are formed and released into the atmosphere, which affect the increase in surface temperatures. According to the data in figure 1.1 published by British Petroleum, carbon dioxide emissions in Kazakhstan have tripled over the past 70 years. Air pollution negatively affects the condition of soil and water resources by polluting atmospheric precipitation [4].

The above factors are only part of the problems that are caused by the extraction and consumption of fossil fuel resources. Therefore, developed countries are actively developing and introducing biofuel resources into technological use. These resources during the combustion process do not contribute to the release of high contents of carbon dioxide and sulfur (not higher than 0.16%), are renewable and are easily accessible. The formation and emissions of nitrogen oxides are minimal. This process is explained by the lower combustion temperature of plant waste.

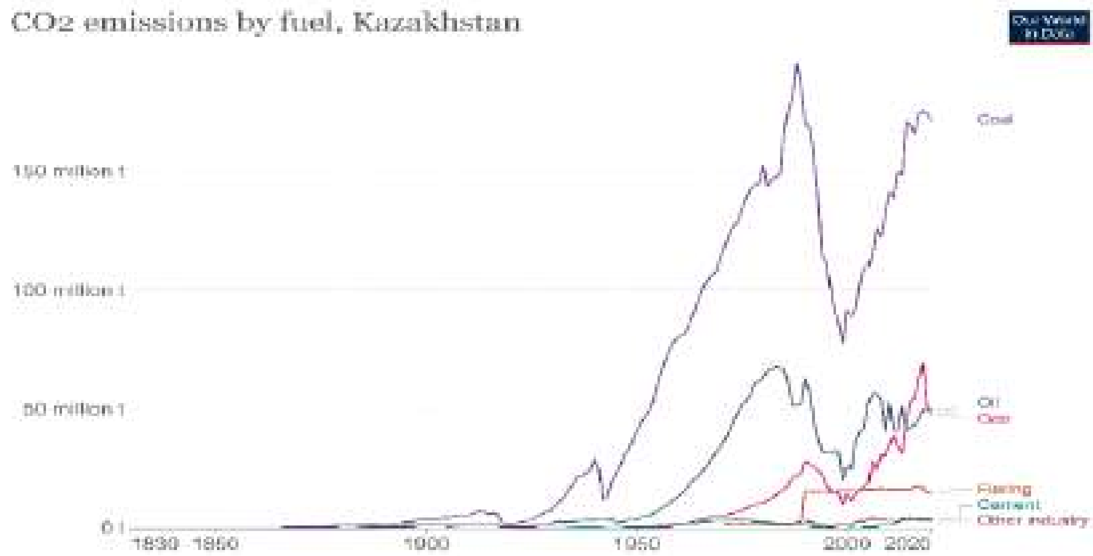


Figure 1.1 – CO_2 emissions in Kazakhstan for all types of fuel

The widespread use of plant waste is one of the leading solutions to combat the reduction of CO_2 emissions. This is justified by the fact that when burning biomass, which consists of plant waste, the same amount of CO_2 is released that was absorbed by the plant during its life cycle. In this way, the released carbon dioxide is recycled without increasing its content in the atmosphere. An important factor is also the minimal presence of sulfur oxides in plant waste.

Many production processes generate huge amounts of industrial waste, which can be used as energy resources, for example, fuel [5].

More than 2 billion tons of waste are produced annually in European Union member states, and this figure is growing steadily. According to the Statistical Office of the European Union, the main sources of waste are construction (32.9 %), mining (27.8 %), manufacturing (13.1 %) and households (8.5 %) [6].

Industrial waste is varied in its properties and composition: pieces of metal, metal shavings, waste oil products, mineral parts of raw materials and fuel, metallurgical slag, ash, dust, etc. The amount of waste generated depends on the technology, quality of raw materials and the processes of the production organization of the enterprise.

Today, the technical and production process is developing, the demand for industrial products is increasing, and humanity is growing globally. The generation of industrial waste that needs to be disposed of or recycled is constantly increasing [7, 8].

In Kazakhstan, even with the presence of numerous industrial enterprises, the issue of processing generated industrial waste has never been acute. The main types of industrial production with the largest amount of waste are mining and manufacturing. All waste is stored mainly in areas close to enterprises, polluting the environment.

After time, the question arises about processing these types of waste. New technologies, equipment and machinery for processing industrial waste have appeared, which give industrial waste a second life.

Recycling industrial waste has become much more profitable than disposing of it. Almost all industrial waste can be used for the benefit of society, for example, pieces of metal formed in the process of manufacturing metal products can be packaged, briquetted and melted into new metal. Waste generated during the construction process (pieces of concrete, brick, plaster, etc.) can be recycled and used in the future for filling roads, courtyards and for many other purposes. Large motor transport enterprises generate waste in the form of worn-out tires, which can also be recycled into crumb rubber and used for the construction of stadiums, playgrounds and other socially significant facilities [9].

On the other hand, an impressive volume of agricultural waste is generated annually in Kazakhstan, the energy potential of which is not realized. Almaty (979.9 thousand tons/year), Zhambyl (716.7 thousand tons/year), Akmola (854.0 thousand tons/year), Kostanay (877.8 thousand tons/year) and North Kazakhstan (890.7 thousand tons/year) regions. The total production volume of waste and residues of oilseed production throughout Kazakhstan is 1,123.5 thousand tons/year. The leaders in available waste are South Kazakhstan (296.0 thousand tons/year), East Kazakhstan (226.1 thousand tons/year), Almaty (187.0 thousand tons/year) and North Kazakhstan (145.2 thousand tons/year), Pavlodar (48.4 thousand tons/year) region [10].

About one billion tons of industrial waste are generated annually in Kazakhstan. The leaders are the following regions: Karaganda (110 million tons per year) and Pavlodar (104 million tons per year). In total, the share of accumulated industrial waste in Kazakhstan is 31.6 billion tons [11]. The main sources of pollution in the Pavlodar region are large industrial enterprises in the energy, metallurgy, chemical, coal mining and oil refining industries. By-products of these industries include coal processing waste, coke residues, and the huge formation of ash and slag waste.

However, the implementation of the use of industrial and agricultural (plant) waste as an alternative to traditional sources is difficult due to little knowledge of the properties and characteristics of these wastes.

1.2 Main characteristics of briquettes from vegetable waste

As a material for creating briquette fuel, plant waste from the agricultural industry and industrial waste are used in various proportions.

Let's consider the main characteristics of fuel briquettes.

1) Increased heat dissipation:

a) A fuel briquette consists of small particles, due to which during combustion the briquette is more permeable than a monolithic piece of coal, for example. The briquette burns completely. Result: fuel savings of 30%.

b) Reduced moisture content due to heat treatment of briquettes. Steam losses are minimized. Result: 5 % fuel savings.

c) The shape and dimensions of the briquette ensure high permeability of the bulk layer during layer combustion. Result: 5% fuel savings.

2) Environmentally friendly products. Our study did not include any special additives. The lignin contained in the raw material will serve as a binder. Therefore, there will be no damage to the environment from this side.

3) Cleanliness. The products are packaged in cardboard boxes (bags). Carefully packaged briquettes can be stored in a coal warehouse, while occupying 2 – 3 times less space. Consequence: saving space in utility rooms.

4) No losses during transportation and transshipment. Coal losses during transportation and loading reach up to 20 %.

5) It is easier to maintain the combustion process in the furnace. There is no phenomenon of coal caking in the layer due to a more uniform distribution of crushed ash residue in the briquettes. Consequence: simplified maintenance of stoves and fireplaces and fuel savings of 2.5 %.

Plant waste has sufficient energy potential to realize its use as fuel. The cellular composition of agricultural plant waste contains lignin. When heated and pressed, lignin becomes plastic and sticky, acting as a binding component. As a result, strong adhesion of small fractions occurs and the strength of the resulting briquettes increases [12].

Plant waste has the following characteristics:

1) Low ash content, within A = 2 % to 12 %;

2) Low sulfur content, ranging from S = 0.02 % to 0.2 % and nitrogen N = from 0.3 % to 1.2 %;

3) The release of carbon dioxide during the combustion of plant waste occurs in exactly the same volume as was absorbed by the plant during its life cycle;

4) Heat of combustion of organic waste Q = up to 20 MJ/kg;

5) The production of vegetable fuel does not have a negative impact on the soil structure [13].

It is necessary to take into account a number of characteristics inherent in plant waste before using it as raw material for fuel briquettes. The main characteristics include moisture content, ash content, elemental composition, and heat content.

Moisture content is an important factor in briquette formation. High moisture content in the raw material complicates the briquette formation process, affects its density and reduces the calorific value. Too low humidity will negatively affect the process of pressing raw materials. The adhesion between particles will be worse.

Numerous studies of various agricultural wastes have shown that there are small differences between them in terms of thermal characteristics. Below is a comparative description of some types of plant-based agricultural raw material waste (table 1.1).

Table 1.1 – Thermal characteristics of some agricultural wastes [14]

Sample	Humidity, %	Ash content, %	Heat of combustion, J/kg
Sunflower husk	8.40	2.70	16 – 20
Oat husk	9.80	4.78	14 – 19
Buckwheat husk	6.50	7.95	15.82
Barley straw	7.40	5.90	17.00
Corn stover	7.96	5.10	19.00
Millet	7.92	5.70	18.00
Cotton	4.43	15.50	14.5

Based on the results of the analysis of the presented data the following conclusions can be drawn. Thermal characteristics of different types of biomass vary within small limits. All types of plant raw materials have fairly high calorific values. The lowest ash content is observed in sunflower husks – 2.7 %. Therefore, it has the highest calorific value (up to 20 MJ/kg). Cotton has the highest ash content of 15.5 %, which significantly reduces its calorific value. The lowest moisture content was observed in buckwheat husks – 6.5 %, the highest percentage of moisture was in oat husks – about 10 %.

Table 1.2 – Elemental composition of agricultural waste [14]

Sample	Carbon, %	Sulfur, %	Hydrogen, %	Nitrogen, %	Oxygen, %
Sunflower husk	50.1	0.14	6.3	1.7	41.4
Oat husk	42.7	0.23	5.8	0.9	52.7
Buckwheat husk	48.3	0.2	6.57	0.7	45.65
Barley straw	46.9	0.1	5.3	0.7	41.0
Corn stover	43.7	0.1	6.1	0.5	44.6
Millet	45.5	0.1	6.1	0.9	41.7

The presented wastes have a similar elemental composition. The highest carbon content was observed in sunflower husks (50.1 %), the lowest value was typical for oat husks (39.8 %), the carbon content of coal varies around 60 %. The content of sulfur and nitrogen in the presented waste is extremely low for all types and is in the same range. This guarantees lower emissions of these oxides into the atmosphere than when burning coal fuel, in which the sulfur content can reach up to 8 %.

Biomass intended to be used to create a fuel briquette must meet a number of requirements that will ensure the effectiveness of its use as a fuel material. In the studies of the authors [15], [16], the optimal ranges of characteristics that apply to fuel briquettes were established (table 1.3).

Table 1.3 – Optimal characteristics of fuel briquettes

Characteristic	Parameter	Indicator
Physical	Density, g/cm^3	0.24 – 0.37
	Moisture contents, %	5.55 – 12.33
	Water resistance,%	87.60 – 92.0
Mechanical	Destruction index, %	86.00 – 99.08
	Withstand pressure, MPa	18.47 – 21.75
Thermal	Heat of combustion, MJ/kg	12.0 – 17.0
	Volatile yield, %	68.20
	Ash content, %	16.10
	Fixed carbon, %	15.70
Elemental composition	Carbon, %	45.20
	Hydrogen, %	5.80
	Nitrogen, %	1.02
	Oxygen,%	47.60
	Sulfur, %	0.21

The characteristics of fuel briquettes are divided into mechanical, physical and thermal. They completely influence the quality of briquettes, determine the ability of briquettes to withstand external influences and behavior during the combustion process. A high-quality briquette must have strength (physical) characteristics that ensure safe transportation and storage, eliminating the possibility of damage to its structure.

Thermal characteristics must be within optimal ranges to ensure safe and beneficial use of the briquette during the combustion process. Excessive or low specified thermal characteristics can negatively affect the combustion process and the calorific value of the briquette.

The elemental composition of the combustible part must guarantee the rapid reactivity of the briquette during the ignition process. The briquette must contain a sufficiently high percentage of volatile matter. The content of elements such as nitrogen and sulfur in the fuel briquette should be minimal in order to minimize the amount of harmful emissions.

Based on the analysis of the thermal and elemental characteristics of various biomass samples, and comparison with the above optimal characteristics for briquetting (table 1.3), we can conclude that the presented agricultural waste meets the requirements.

1.3 Research experience in the field of briquetting agricultural and industrial waste

The technology of briquetting various wastes originated in the mid – 19th century. The technology for producing briquette fuel from charcoal and coal was developed by A.P. Veshnyakov, followed by A.I. Shpakovsky invented a method for creating briquettes from peat. Currently, various researchers have been studying the characteristics of agricultural and industrial waste. Some of the studies are reviewed and analyzed in this work.

The article [17] analyzed the combustion quality of briquettes made from various agricultural wastes (coconut, rice, coffee husks and sawdust). The waste was pre-dried in the sun for two to eight hours to reduce moisture content and ground into smaller fractions, excluding sawdust. Figure 1.2 summarizes the characteristics of all briquettes obtained during the experiments.

The ash content of coffee husk bio-briquettes is the lowest value (0.60 %) and rice husk has the highest value (15.63 %). It is known that the lower the ash content, the greater the calorific value. The moisture content of coconut husk has the lowest value (1.56 %) and rice husk has the highest value (7.38 %). Volatile substances, which are responsible for the reactivity of any fuel, turned out to be in a fairly wide range. Coconut husk briquettes have the lowest volatile matter yield (22.11 %) and rice husk briquettes have the highest volatile matter yield (58.20 %).

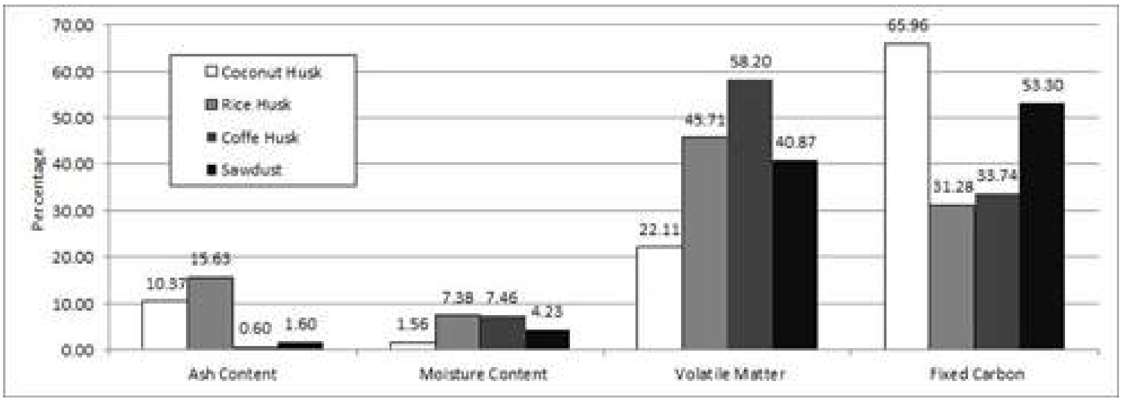


Figure 1.2 – Obtained characteristics of briquettes from various agricultural wastes [17]

In tests to determine the lower calorific value of briquettes, the highest value was recorded for coconut husk (22 068,73 kJ), the lowest value was for rice husk (14 036,5 kJ). However, the calorific value was higher than that of some charcoals. The calorific content of coffee husks (16 948,55 kJ) and sawdust (17 794,93 kJ) are comparable to each other. All results were compared with the calorific value of stone (25 802,02 kJ) and charcoal (13 232,02 kJ).

In [18], a study was carried out on briquettes consisting of waste leaves of Pterocarpus Indicus. Tapioca was used as a binder in various percentages. The highest calorific value was shown by the composition of briquettes with a ratio of 90 % leaf waste and 10 % tapioca (19475.75 kJ/kg). The main characteristics of the above-mentioned briquette were determined (table 1.4).

Table 1.4 – Characteristics of briquettes made from leaf waste

Parameter	Meaning
Moisture content, %	5.20
Ash content,%	6.20
Volatiles, %	73.30
Sulfur content,%	0.25
Carbon,%	49.12
Hydrogen, %	6.60

The results obtained from studying the characteristics of tapioca briquettes and leaves are within the optimal (in accordance with table 1.4) limits for almost all parameters or slightly exceed them. The high content of volatile substances in the briquette composition has a positive effect on its ignition rate.

In article [19], thermal analysis of fuel briquettes consisting of coal dust and peanut husks was carried out. For different ratios of coal dust and peanut husk content in a briquette, the main characteristics were determined. The best values of lower calorific value changed slightly (from 25027.18 kJ/kg to 21714.17 kJ/kg). As the peanut hull content in the briquette increased from 10 % to 100 %, the ash content (from 24.18 % to 29.15 %) and moisture (from 2.43 % to 6.44 %) increased. The amount of volatile substances is also increasing (from 20.17 % to 47.64 %). Analysis of the combustion of briquettes containing a pulverized coal mixture and peanut husks in a ratio of 10 % to 100 % showed the following data: the ignition time was reduced (from 45.2 s to 22.23 s) and the burning time of the briquette (from 28.32 s to 16.10 s). Based on the results obtained, the researchers concluded: the optimal ratio of component contents for making briquettes from coal dust and peanut husks is 60:40. This briquette showed the following results: high strength – 10.8 N/mm^3, calorific value – 23628.8 kJ/kg, briquette burning time – 22.56 minutes, ignition time – 35.7 seconds.

The study [20] looked at the production of briquettes consisting of waste plastic, acacia bark and waste oil. The ratios of components and the results obtained during the experiment are shown in table 1.5.

Table 1.5 – Characteristics of briquettes made from plastic, bark and waste oil [20]

Mixture ratio (plastic : oil : bark)	Density, kg/m^3	Moisture, %	Ash, %	Volatile substances, %	Fixed carbon, %	Sulfur content, %
40:60:100	0.79	3.58	2.41	85.15	8.86	0.13
25:70:100	0.68	5.45	2.80	80.37	11.38	0.17
30:70:100	0.70	3.43	2.19	86.26	8.12	0.16
35:70:100	0.70	3.12	2.85	84.62	9.41	0.16
40:70:100	0.79	3.66	2.57	85.04	8.73	0.20
20:80:100	0.67	4.93	2.51	82.32	10.24	0.18

As a result of analyzing the table, the following conclusions can be drawn. Increasing the plastic content has a positive effect on the density and moisture content. The large amount of bark waste contained in the briquette leads to an increase in the content of ash and fixed carbon. Adding oil to the briquette increases the sulfur content.

During experimental studies, the heat content of various options for briquette mixtures was determined (table 1.6).

Table 1.6 – Calorific value of briquettes made of plastic, oil and bark

Mixture ratio (plastic : oil : bark)	Lower calorific value, MJ/kg
10 70 120	27.11
20 60 120	27.00
20 80 100	30.00
40 70 100	32.70
35 70 100	33.26
30 70 100	33.56
25 70 100	30.11
40 60 100	30.46

The highest calorific value (33.56 MJ/kg) was determined for a briquette with the component ratio: 30 % plastic, 70 % oil, 100 % bark. The briquette with the best mixture content in terms of heat of combustion also has the best results in terms of moisture content (3.43 %), ash (2.19 %) and the amount of volatile substances (86.2 %). In general, the calorific value of all briquettes obtained is high and meets the quality requirements.

In the study [21], the authors produced a fuel briquette from biomass containing oat husk as a solid base; the binder material was oat husk flour. The briquette was made in the following ratio: from 80 % to 90 % oat husks, from 10 % to 15 % binding material (oat husk flour), the rest was water.

A distinctive feature of this method is the heating of the mixture to 200 °C during the briquetting process. The briquettes were pressed at a pressure from 1000 to 1200 kgf/cm^2.

Due to heating, the surface of the briquette was covered with a film, which gives a water-repellent effect. Characteristics of oat biomass briquettes are presented in table 1.7.

Table 1.7 – Thermophysical characteristics of oat husk briquettes

Humidity, %	Density, kg/m^3	Heat of combustion, MJ, kg	Ash content, %
8–10	600–750	20,0–24,0	2–3

The resulting briquette has good thermal characteristics. The combustion heat reached 24.0 MJ/kg, the ash content was 2 %. High strength characteristics will ensure its safe transportation, without crumbling.

In work [22], issues of briquetting technology from coal mining and coal processing waste are studied and presented. Coal and coke dust were taken as raw materials for yurikets. Experimental tests were carried out to determine the thermal properties of briquettes made from enriched coal and coke dust using the oil agglomeration method.

Coke dust and coal dust with a fraction size of less than 1 mm and an ash content of 18 % to 30 % were mixed in a 1:1 ratio. The fuel mixture was enriched with waste exhaust oil. Coking fuses heated in the range from 50 °C to 60 °C were used as a binding material. The fuel mixture was pressed for three minutes with gradually increasing pressure from 5–6 atm to 15 atm. The parameters of the resulting briquette are presented in table 1.8.

Table 1.8 – Characteristics of pressed coke dust without the use of a binder and fuel briquettes with a binder [22]

Type	Ash content, %	Calorific value, kJ/kg	Sulfur content, %
Pressed coke dust	12.0–16.8	37 291.0–38 757.5	0.04–0.05
Briquette with binder	5.0–5.5	35 824.5–36 034.0	0.25–0.3

In the course of the study, it was established that the permissible presence of the binding component is 8 % of the total fuel mass. Despite a slight decrease in the calorific value of the briquette with the addition of a binding component, the ash content in it decreased significantly from 16.8 % to 5.5 %. The strength characteristics increased significantly with the addition of fuses. However, despite the positive side, the addition of fuses to the briquette composition resulted in an increase in the percentage of sulfur content. However, the obtained result slightly exceeds the optimal requirements. Unfortunately, this study lacks a plant component in the mixture.

The manuscript [23] discusses the technology for the production of fuel briquettes from raw material waste from coke production (coke dust and coking slurry). The production of briquettes was carried out in two ways: in the first method, the mold was heated to 50 °C and pressed stepwise, reaching a pressure of 15 atm. The second method was carried out without heating the mold, but the coconut dust and fus were heated to 100 °C. The ratio of the binder component and coke dust was 8 % to 92 %. The data obtained during the experiment were recorded in Table 1.9.

Table 1.9 – Characteristics of two types of briquettes [23]

Receiving method	Compression, kg/cm^2	Ash content, %	Sulfur content, %	Heat of combustion, MJ/kg
First way	50–60	6.4	0.45	39.805
Second way	60–90	6.5	0.48	39.805

It was found that technology in both cases had a positive effect on the quality characteristics of the briquette. The ash content in briquettes is within the same limit and, in comparison with the ash content of the source material (from 10 % to 16 %), they are significantly lower. Higher strength characteristics (from 60 to 90 kg/cm^2) were found in briquettes made using the second method using preheating of the mixture. Heating the mixture improved the adhesion of the components to each other. The heat of combustion of the resulting two briquettes exceeded the initial heat of combustion of coke dust from 37.710 to 39.805 MJ/kg.

This method allows you to use waste from coke plants that is not yet used. This study also lacks a plant component in the mixture.

In article [24], the authors determined the thermal characteristics of the products of low-temperature pyrolysis (400 °C) of low-lying peat from various deposits (Sukhovskoye and Arkadyevskoye deposits, sample obtained from the State Scientific Institution SIBNIISKhiT).

The moisture content of the samples was not determined due to the fact that the raw material was subject to pyrolysis at a temperature of 400 °C. The characteristics obtained during the experiment are shown in table 1.10.

Based on the data obtained, the ash content of the raw materials listed is quite high, which negatively affects the combustion process. The yield of volatile substances in all samples was high, which has a positive effect on the speed and ease of ignition of the briquette. The resulting fuel briquettes had a calorific value much higher than that of the original raw material. For example, the heat of combustion of a fuel briquette from low-lying peat from the Sukhovsky deposit was 6.5 times higher than the initial parameter (2.7 MJ/kg).

Table 1.10 – Characteristics of briquettes made from raw materials of low-temperature pyrolysis of low-lying peat

Briquette type	Ash content, %	Heat of combustion, MJ/kg	Volatile yield, %
Raw materials for low-temperature pyrolysis of low-lying peat. Sukhovskoye	32.2	17.7	82.6
Raw materials for low-temperature pyrolysis of low-lying peat. Arkadyevskoye	48.0	14.0	89.6
Raw materials for low-temperature pyrolysis of low-lying peat. SIBNIISKhiT	33.3	20.7	55.7

In article [25], the process of conductive pyrolysis of sunflower husks was studied and the characteristics of the resulting briquettes were determined. 30 grams of raw material were pressed with a pressure of 0.5 to 3.0 tons. Next, the sample was heated to 450 °C and held for 20 minutes. Based on the results of the test, it was found that the ash content in the resulting briquettes was 6.2 %. The maximum density of the briquettes was 1139 kg/cm^3 (the original density of the sample was 90 kg/m^3), with a pressing pressure of 153 kg/cm^2.

1.4 Briquetting of industrial waste: review of technologies

A review of existing methods and technologies of briquetting shows that at an early stage of development it was used for agglomeration of coals, then used for agglomeration of primary metallurgical raw materials – fine ore, coarse concentrates. In the mid-twentieth century, briquetting was used mainly for the atomization of crushed and dusty waste, which was associated with the difficulty of agglomerating them using other methods.

Briquetting waste has a number of advantages compared to using it in its original form. First of all, the vehicle load factor increases and the production culture improves. Briquettes are easy to use, they can be burned in home stoves and fireplaces, and used for heating housing and communal services.

The standard briquette production technology is shown in figure 1.3.

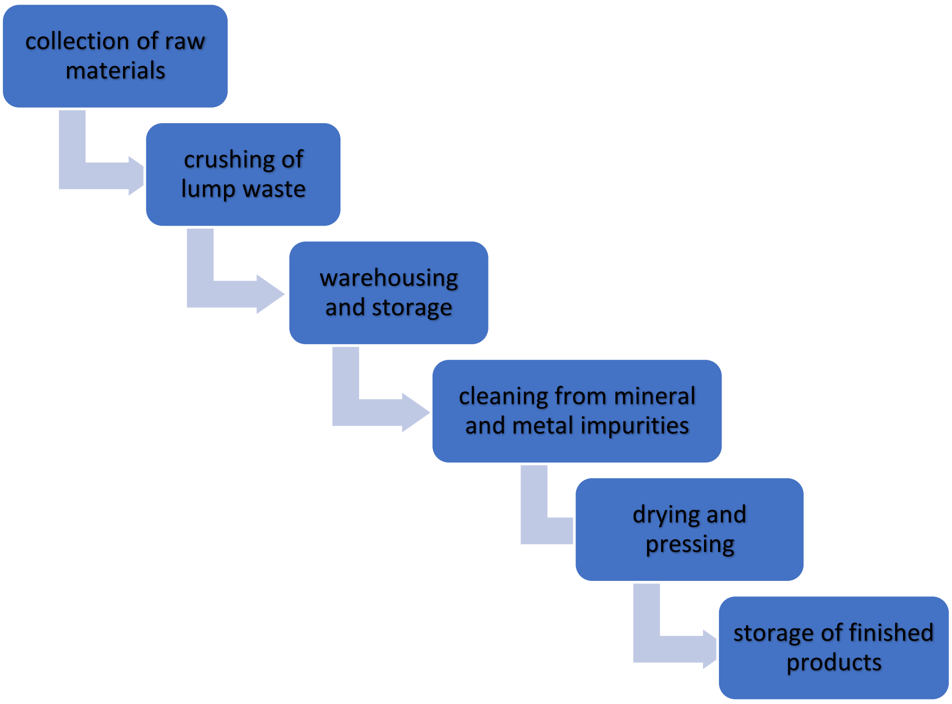


Figure 1.3 – The standard briquette production technology

The main unit in the technology is the pressing unit. Presses are hydraulic and mechanical.

The mechanism of the main stage of briquetting – pressing in general form is presented as follows. At low pressure, external compaction of the material occurs due to the voids between the particles. Then the particles themselves become compacted and deformed; molecular adhesion occurs between them. High pressure at the end of pressing leads to the transition of elastic deformations of the particles into plastic ones, as a result of which the structure of the briquette is strengthened and the specified shape is maintained.

The briquetting process can occur without binders or with the use of binders. Binders are inorganic and organic. Inorganic ones include: lime, clay, gypsum, cement, magnesite, tripoli, alkalis, sodium and calcium phosphates, granulated blast furnace slag, cast iron shavings, etc. These substances are used both individually and in mixtures.

Organic binders include: coking coal, pitch, tar, resins and various wastes from the pulp, paper and food industries, for example, sulfite liquor, molasses, etc.

Let's look at some of the stages of briquetting in more detail:

- Drying.

Moisture content is very important both in terms of briquette strength and heat content. A distinction is made between direct drying (high-speed dryer using hot gas) and indirect drying (disc dryer using heat from steam).

- Grinding.

Raw materials usually require grinding for better particle adhesion and higher briquette strength.

- Binders.

Binders are necessary to increase the strength of the briquette and its suitability for further transportation and use. Typical binder content ranges from 5 % to 15 % of the total mixture weight.

- Production of briquettes.

The prepared mixture is fed to the press. The shapes of briquettes can be different depending on the type of roller recesses. The most common briquette shape is a pillow shape.

Modern technologies for the production of fuel briquettes pose the following tasks:

1) Production of briquettes with properties that are required by a specific customer. The final product (briquette) must have the desired configuration, size, shape, and also have good physical properties.

2) Production of briquettes with a given energy value (thermal potential). This issue also takes into account the needs and conditions of the customer.

3) High production capacity and speed

4) Minimizing costs for the production of fuel bricks and reducing the number of personnel to ensure the operation of production.

Let's consider the option of briquetting waste from coke production: coke breeze and coke dust. Coke breeze is not directly used without additional processing due to its finely dispersed state and high ash content, and difficulties with unloading and transportation. On the other hand, the problem of recycling coke breeze is very promising, but requires careful development of technology and selection of equipment.

Coke breeze, and especially coke dust, require special preparation for recycling. One of the preparation methods is agglomeration. Known methods for agglomerating dust: granulation, briquetting and tableting.

To produce briquettes or tablets from petcoke breeze with a binder, the following equipment is required:

1) mixer-heater for uniform distribution of the binder and heating the mixture to the pressing temperature;

2) dispenser for the resulting mixture or heated raw materials;

3) briquetting or tableting machine;

4) a container for cooling briquettes or tablets;

5) conveyor;
6) packing machine.

In the case of the production of briquettes from petroleum coke breeze without a binder, instead of a mixer-heater, a device for heating the coke breeze in a flow of hot gases is required.

The coke breeze briquetting plant can be equipped with a drying unit to ensure the required moisture content of the raw material before feeding it into the mixer.

The pressing pressure of briquettes depends on the chosen technology and type of binder and can be (according to literature data) in the range from 0.3 to 25 MPa.

The study [26] proposed a new design of a hydraulic stamp press designed for briquetting coal and coke fines. Figure 1.4 shows the general diagram of a briquette stamp press and its cross-section.

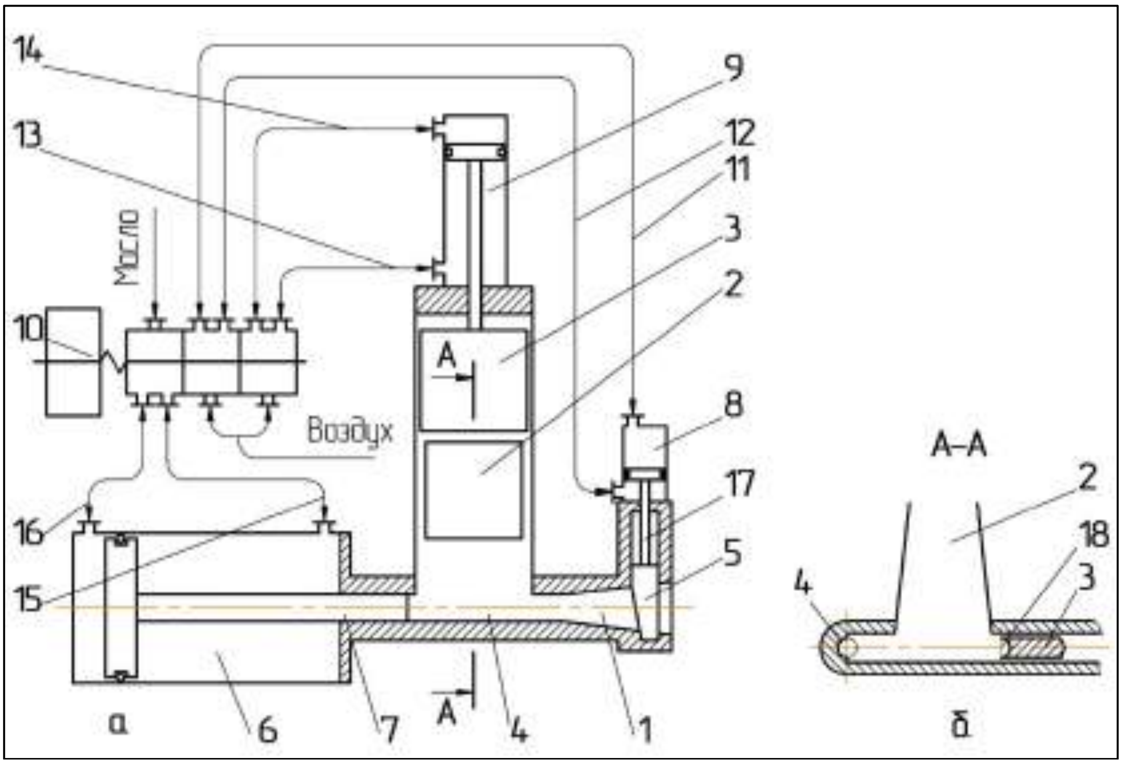


Figure 1.4 – Diagram of a briquette stamp press [26]

The press consists of a stamping chamber 1 for forming briquettes, a loading chamber 2 with a raw material supply piston 3, a pre-pressing chamber 4, and a damper 5 of the stamping chamber.

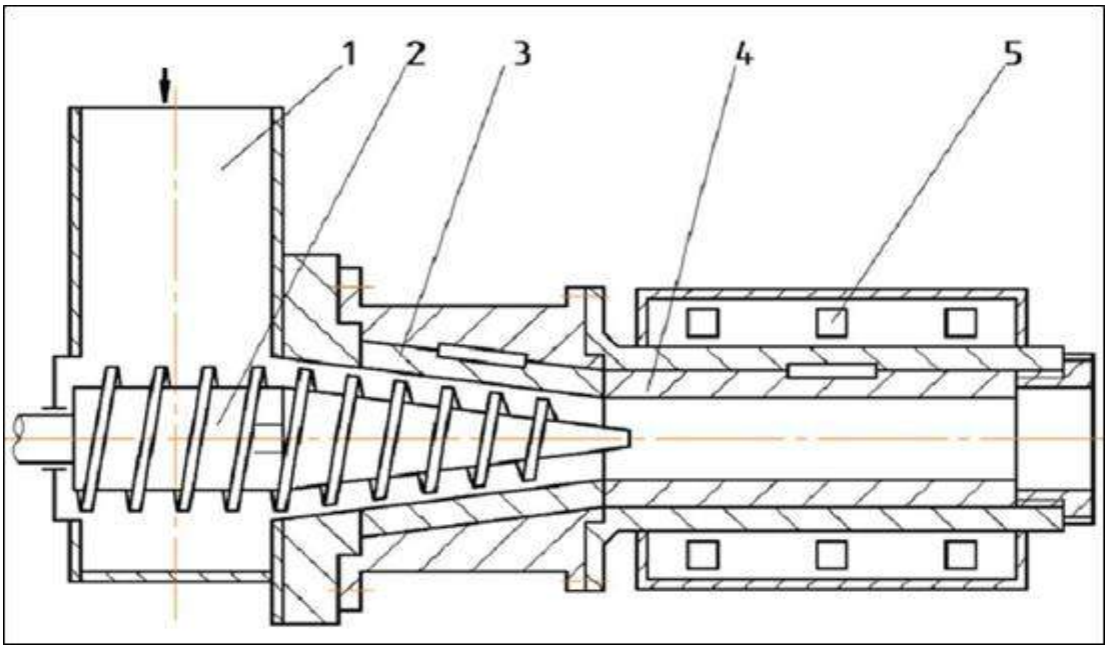
The briquette press also contains a hydraulic cylinder 6 for the pressing actuator with a rod 7, a pneumatic cylinder 8 for the actuator for raising and lowering the damper 5 of the stamping chamber 1, a pneumatic cylinder 9 for the actuator for the raw material supply piston 3 and a device 10 for coordinating their control. The device 10 for coordinating the control of their operation is connected by pneumatic lines 11 and 12 to the pneumatic cylinder of the stamping chamber damper, pneumatic lines 13 and 14 to the raw material supply pneumatic cylinder, and hydraulic lines 15 and 16 to the hydraulic pressing cylinder. The mechanism for raising and lowering the damper 5 of the stamping chamber 1 contains a pneumatic cylinder 8, the rod 17 of which is connected to the damper 5.

The press works as follows. The initial position of the rod 7 of the piston 3 for supplying raw materials, the damper 5 of the stamping chamber 1 is shown in figure 1.4. In this case, loading chamber 2 is filled with raw materials. When the control coordination device 10 is turned on, air is supplied through the pneumatic line 14 to the pneumatic cylinder 9 of the actuator of the raw material supply piston, and through the pneumatic line 13 it is removed from it, and the piston 3 moves and supplies the raw material to the pre-press chamber 4. The pre-press chamber 4 is filled with raw materials.

Since the density of the briquette will depend on the pre-press pressure in chamber 4, this pressure is regulated by the stroke of the raw material supply piston 3, which is regulated by the pneumatic cylinder 9. At the end of its stroke, piston 3 closes the pre-press chamber 4 to form a cylindrical channel with a diameter larger than the diameter of the rod. The piston 3 stops, the coordination and control device 10 supplies hydraulic fluid through the hydraulic line 16 to the hydraulic cylinder 6 of the pressing actuator, and removes it through the hydraulic line 15, the rod 7 moves and compacts the raw material, first in the pre-pressing chamber 4 and finally in the stamping chamber 1.

When the required pressure in the hydraulic cylinder is reached, hydraulic cylinder 6 is transferred to the “floating” position (the rod does not press and can move). Air is supplied to the pneumatic cylinder 8 of the actuator for raising and lowering the damper 5 through the air duct 12 (and removed through the air duct 11), and through the rod 17 it opens the damper 5 of the stamping chamber. After opening the damper 5, pressure is again supplied to the hydraulic cylinder 6 and the rod 7 pushes out the briquette. The rod 7 and the damper of the stamping chamber 5 return to their original position. The raw material supply piston 3 returns to its original position as soon as the hydraulic cylinder 6 stops in the floating position. Then the process is repeated. Instead of air, hydraulic fluid can be used as a working agent in all actuators.

The operating principle and diagram of an extruder (screw) briquetting press is presented in figure 1.5 [27]. The form of the stamping chamber allows the output to be a briquette of equal density along the length.



1 – loading pipe; 2 – feed screw; 3 – pressing screw; 4 – matrix channel; 5 – heating elements [27]

Figure 1.5 – Operating principle and diagram of an extruder (screw) briquetting press

Briquetting of coke breeze and dust using extruders is recommended, for example, in [28]. Extruder briquetting machines for coke breeze are produced by Ukrainian [29] and Chinese manufacturers [30]. Of all the known briquetting machines, the most productive are roller briquetting machines. Considering the large volumes of coke breeze to be processed, it is roller machines that are of the greatest interest.

The operating principle of roller briquetting machines is shown in figures 1.6 and 1.7.

To summarize, the following things can be stated. Firstly, the considered thermal characteristics of various agricultural wastes prove that biomass is a good alternative to traditional energy sources. Secondly, the existing experience of foreign and domestic researchers in the field of briquetting proves the effectiveness of using plant and industrial waste as feedstock.

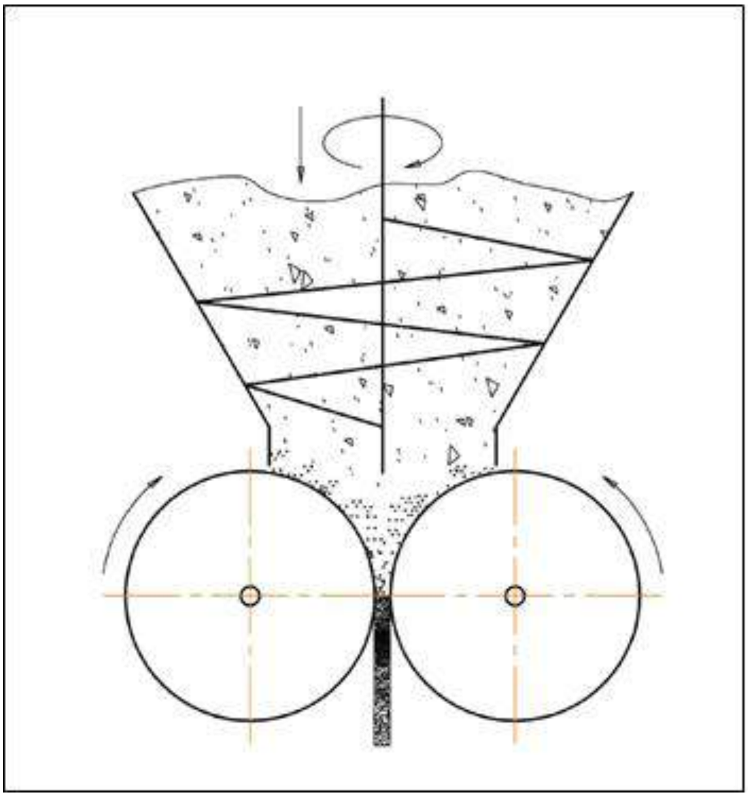


Figure 1.6 – Briquetting machine with smooth rollers

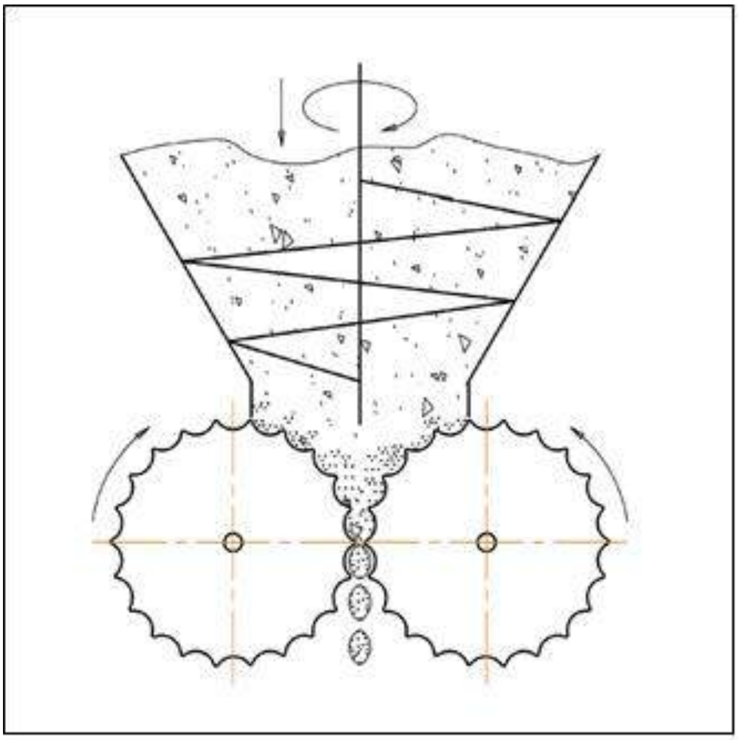


Figure 1.7 – Roller press with a screw feeder, which additionally compacts the briquette mixture

2 Materials and methods for studying the thermal characteristics of combined fuel briquettes

2.1 Analysis of the raw material base of the Republic of Kazakhstan for agricultural and industrial waste

2.1.1 Disposal of agricultural (crop) and industrial waste is a pressing problem throughout the world. To solve this problem, it is proposed to use waste from these production sectors to obtain thermal energy based on briquetting technology.

Agricultural waste is subject to a wide range of different conditions. The main factors influencing the amount of crop residues are the type of crops planted and their yield. In Kazakhstan, the most important crops in terms of production volumes are wheat, barley, corn and rice. The harvested area of the listed agricultural crops is 35 million hectares.

There are several requirements for the successful use of crop waste from the agricultural sector:

- the cultivated share of land must exceed 50 %;
- stable annual harvest level;
- favorable soil condition, sufficient moisture [31].

As vegetable raw materials for the production of combined fuel briquettes, you can use waste generated during the processing of the following grains and oilseeds: buckwheat, sunflower, millet, oats, corn, rapeseed, rice, rye, wheat. In the north of Kazakhstan, grain crops such as wheat, oats, corn, millet, sunflower are grown, and in the south – rice. We will analyze the volumes of the most common agricultural crops in Kazakhstan.

According to data provided by the Statistics Agency of the Ministry of National Economy of the Republic of Kazakhstan for 2011–2021, a steady increase in the area under crops is recorded (figure 2.1). In 2023, the area under agricultural crops amounted to 20.18 million hectares. Of these, grains and legumes – 17.48 million hectares, including wheat – 13.72 million hectares, oilseeds – 2.79 million hectares.

According to the regional agricultural departments, in 2022 the sown area of all agricultural crops in the country will be more than 23.16 million hectares, which is 237 thousand hectares more than the level of 2021. Of these, grains and legumes – 16.11 million hectares, including wheat – 12.5 million hectares. Oilseeds are planned to be placed on an area of more than 3.46 million hectares, fodder crops – on 2.97 million hectares, cotton – on 115.2 thousand hectares.

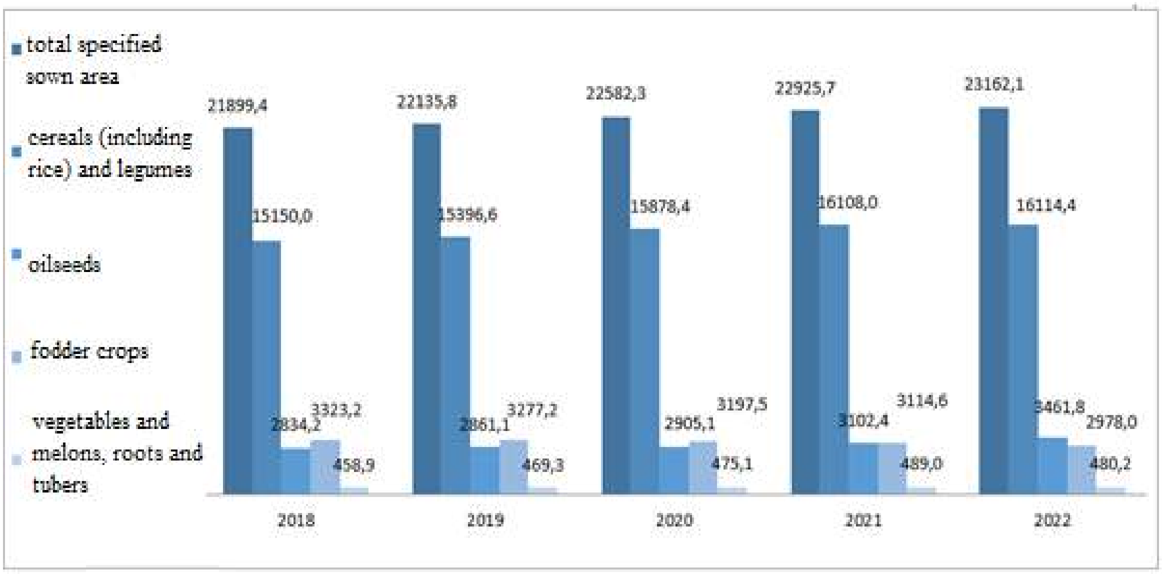


Figure 2.1 – Updated sown area of main agricultural crops [32]

In 2022, the adjusted sown area of grains (including rice) and legumes in the republic amounted to 16,114.4 thousand hectares (at the level of last year), vegetables and melons, root crops and tubers – 480.2 thousand hectares (98.2 % by 2021), of which open ground vegetables – 170.2 thousand hectares (100.9 %), potatoes – 199.5 thousand hectares (101.9 %), cotton – 126.3 thousand hectares (114 ,8 %).

In the Republic of Kazakhstan, the yield of grain and legume crops for 2021 amounted to 16,375.9 thousand tons, oilseed crops – 2,430.1 thousand tons [33]. Of these, the number of sunflower seeds amounted to 1,031.8 thousand tons, in comparison with the cathedral for 2020 (844.3 thousand tons), the amount increased by 18%. The harvest yields of grains (figure 2.1) and oilseeds (figure 2.2) of each region of the Republic of Kazakhstan are presented in the diagrams below.

The gross harvest of main agricultural crops in Kazakhstan in the period from 2018 to 2022 is presented in figure 2.2.

The gross harvest of grains (including rice) and legumes in 2022 increased compared to 2021 by 34.5 % and amounted to 22,030.5 thousand tons, oilseeds – by 25.6 % and 3,051.3 thousand tons, respectively.

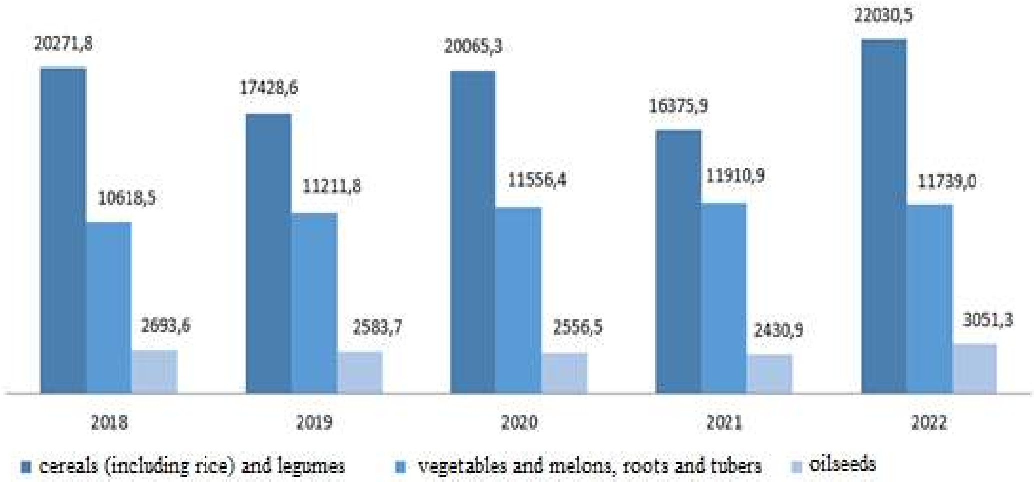


Figure 2.2 – Gross harvest of main agricultural crops in Kazakhstan from 2018 to 2022

The total harvest of some types of grain crops in the Republic of Kazakhstan for 2022 is presented in table 2.1.

Table 2.1 – Total harvest of grains and legumes in Kazakhstan

Grain	Quantity in thousand tons
Wheat	11 814.10
Corn	1 295.50
Oats	182.27
Rice	503.70
Buckwheat	78.04
Millet	35.82

An analysis of Table 2.1 shows that the main share of the harvest of grains and legumes falls on wheat – 11,814.1 thousand tons, the smallest share belongs to millet – 35.82 thousand tons.

The waste generated during the processing of sunflower seeds has the following ratio – 40 % cake and 25 % husk. At the moment, cake and husk are not used on a large scale to produce thermal energy. They are used mainly only as feed and fertilizer.

The gross harvest of grain and legumes in Kazakhstan is presented in figure 2.3.

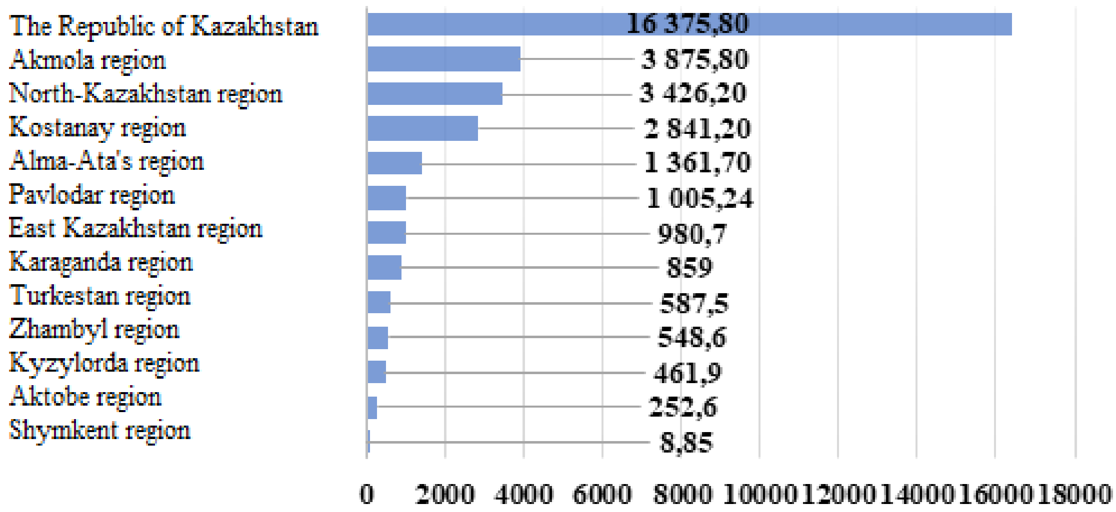


Figure 2.3 – Gross harvest of grains and legumes in Kazakhstan, 2022

Let's analyze the presented data on the collection of grains and legumes for 2022 by region of the country. The leading region in the harvest of grains and legumes is the Akmola region (3,875.8 thousand tons). The smallest collection is observed in the Shymkent region (8.85 thousand tons).

Wheat is the main crop grown in the Akmola region. In 2022, Akmola region occupied a leading position in the harvest of this crop (3,355.0 thousand tons). Almaty region is the leader in corn harvests (660.5 thousand tons). This region is also a leader in barley harvests (452.6 thousand tons). The leader in oat harvest is the North Kazakhstan region (40.97 thousand tons). In addition, the North Kazakhstan region has large volumes of barley (446.3 thousand tons). The Kyzylorda region is the leader in rice harvests (447.95 thousand tons). Rice is the main crop grown in this region. In terms of buckwheat harvests, the main position belongs to the Pavlodar region. In 2022, she collected 43.26 thousand tons of this crop, as well as 22.6 thousand tons of millet.

The possibility of using waste from rice processing is very limited. This is explained by the fact that rice is cultivated only in three southern cities (Almaty, Kyzylorda and Turkestan). The situation is the same with the use of buckwheat husks as raw material for fuel briquettes. Buckwheat is grown only in five regions of Kazakhstan: Akmola, Almaty, Kostanay, Pavlodar, North Kazakhstan and East Kazakhstan regions.

The gross harvest of oilseeds in Kazakhstan in 2022 is presented in figure 2.4.

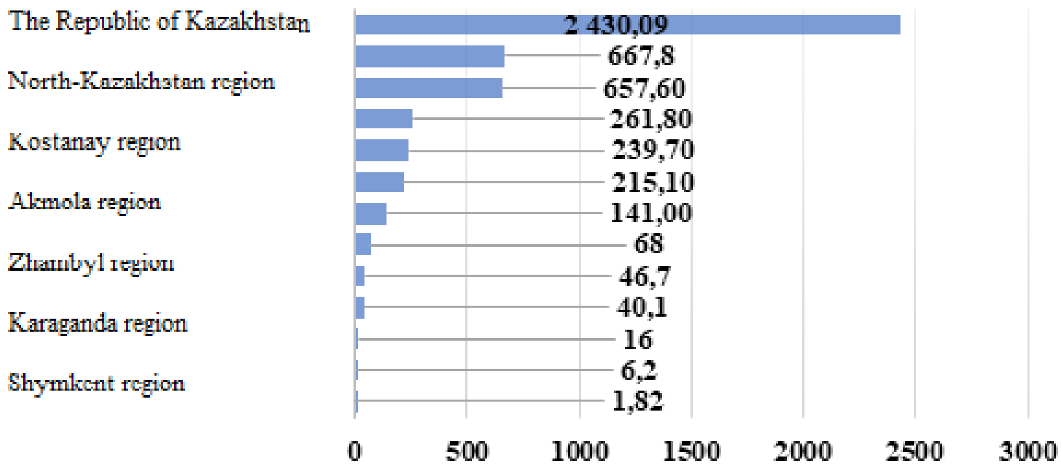


Figure 2.4 – Gross yield of oilseeds in Kazakhstan

Based on data on the gross harvest of oilseeds, it can be argued that the East Kazakhstan and North Kazakhstan regions are the most promising for the disposal of oilseed production waste.

Thus, based on the available data on the harvest of grains and oilseeds, we can come to the following conclusion. From the point of view of forming a raw material base for the production of combined fuel briquettes, the northern and eastern regions of the country have the greatest potential.

Table 2.2 contains information on annual crop production (for 2022) and estimated dry biomass.

Table 2.2 – Estimated dry collection from plant waste in Kazakhstan (for 2022)

Cereals	Harvested dry biomass		Crop production	
	10^6 t/year	%	10^6 t/year	%
Wheat	12.50	53.40	9.56	63.31
Rice	0.51	2.17	0.47	3.11
Corn	7.20	30.75	2.52	16.69
Barley	3.20	13.67	2.55	16.89
Total	23.41	100.00	15.10	100.00

Despite the solid annual cereal production of 23.41·106 tons per year, the total annual dry biomass harvested is 15.10·106 tons per year, accounting for 64.5 %. Of this, 63.31 % is from wheat, 16.89 % is from barley, while 16.69 % and 3.11 % are from corn and rice respectively. The amount of biomass harvested is influenced by crop type, crop waste, and availability factors. For example, wheat accounts for 53.40 % of annual production but 63.31 % of annual dry biomass harvested; however, in the case of corn, although it accounts for 30.75 % of the annual production, the eventual contribution to the harvested dry biomass drops to 16.69 %.

2.1.2 The Republic of Kazakhstan is a developed industrial state. On its territory there are the largest metallurgical complexes (Karaganda, Temirtau, Khromtau, Pavlodar, etc.), three oil refineries (Atyrau, Pavlodar and Shymkent), seventeen large power plants: two thermal power plants in the Almaty region, two thermal power plants in the East Kazakhstan region, six Thermal power plant in the Karaganda region, three thermal power plants and three state district power plants in the Pavlodar region, one thermal power plant in the South Kazakhstan region.

The development of the industrial sector, especially heavy industry, is necessarily accompanied by an increase in environmental pollution. The number of stationary sources that actually emit pollutants into the atmosphere is constantly growing (from 108,576 in 2005 to 227,643 in 2022).

In 2022, the air basin of the republic received such specific pollutants as lead and its compounds in the amount of 213.4 tons, manganese and its compounds – 73.9 tons, copper oxide – 103.1 tons, sulfuric acid – 382.2 tons, chlorine – 53.8 tons, mercury – 264 kilograms. The actual release of these substances did not exceed the volume of established maximum permissible emissions (MPE) (figure 2.5).

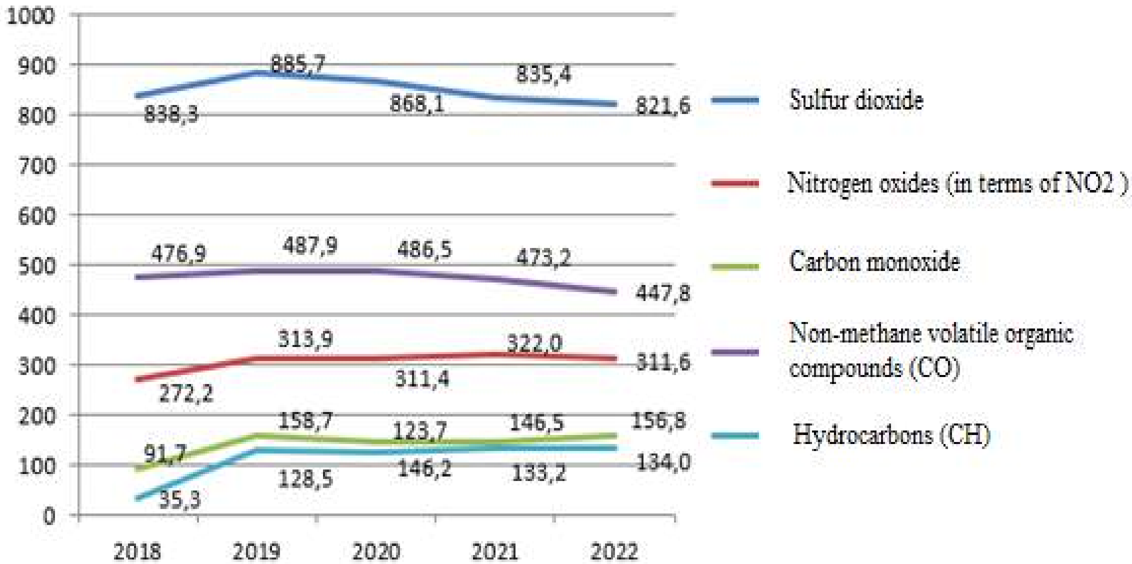


Figure 2.5 – Emissions of main pollutants for 2018 – 2022 (thousand tons) [34]

The main volumes of pollutants were formed in the territories of Pavlodar (724.2 thousand tons) and Karaganda (469 thousand tons) regions.

On the territory of Kazakhstan, in the period from 2005 to 2022, an average of 569.25 thousand tons of solid industrial pollutants were generated annually (according to statistics given in [35]).

The leading regions in terms of the amount of solid waste generated were Pavlodar and Karaganda regions. In the Pavlodar region, over 150 thousand tons of solid industrial waste are consistently generated per year, in the Karaganda region it is slightly less – 110 thousand tons per year. Regions with an average level of solid industrial waste generation include: East Kazakhstan (29.3 thousand tons per year), Akmola (29.1 thousand tons per year), North Kazakhstan (23.8 thousand tons per year) and Aktobe (20 thousand tons per year). In other regions, from 2.3 to 11.0 thousand tons of the mentioned waste are produced per year.

As a result of the activities of the country's industrial sector, about 31.6 billion tons of industrial waste were accumulated. These are mainly man-made mineral formations (TMF), including overburden rock and ash and slag (70% of the total volume), waste from the manufacturing industry (10 % of the total volume) and other activities (20 %). Work on their processing and disposal is carried out at a very low pace. The share of processed and utilized industrial waste in Kazakhstan for the 3rd quarter of 2020 was only 29.7 %.

The remaining volume of industrial waste (about 680 million tons annually) is disposed of in storage facilities and landfills.

The main share of industrial waste comes from mining and enrichment enterprises. They form ever-growing dumps and storage facilities throughout the country. To systematize waste, the State Waste Cadastre was organized. It is a systematized, periodically updated and updated set of unified information for each waste disposal facility. According to the Ministry of Industry and Infrastructure Development of the Republic of Kazakhstan, today 1.5 thousand objects are registered in the State Waste Cadastre.

Typically, waste with small fractions, for example, generated during the extraction and enrichment of coal, shale and peat, and oil and coal refining (coke residue), is used as a raw material for fuel briquettes.

With the annual generation of more than 500 thousand tons of solid waste, the share of recycling is a maximum of 2 % of the total amount. In 2020, 8,186.8 thousand tons of waste were recycled, this figure is 15 % lower compared to the recycling share for 2019 (9,484 thousand tons).

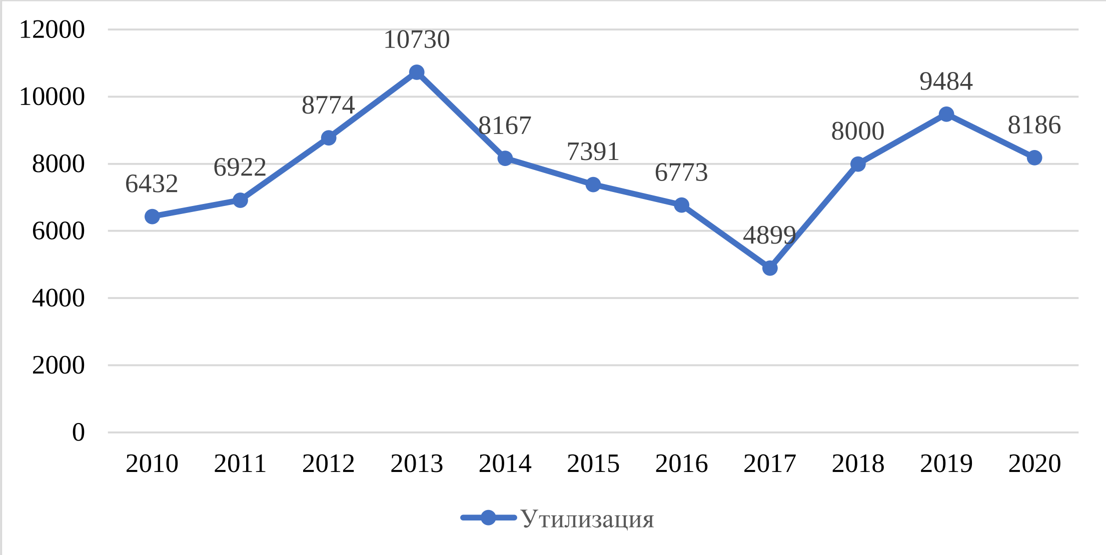


Figure 2.5 – Disposal of solid industrial waste in Kazakhstan 2010 – 2020

According to the data on the amount of solid waste disposed of in the period from 2010 to 2020 (figure 2.5), the following conclusion can be made. Waste disposal indicators are not stable. There is no tendency in the country to increase the percentage of industrial waste recycling. The maximum indicator of processed solids was recorded in 2013 and amounted to 10,730 thousand tons, the minimum in 2017 was 4,899 thousand tons. Between 2017 and 2019, there was a 50 % increase in recycling. However, the data for 2020 are almost equal to the data for 2018, which indicates the lack of sustainable growth in recycling activities.

For further changes for the better in Kazakhstan, it is necessary to take effective measures for the disposal of industrial waste [36]. One of these options could be the recycling of industrial and agricultural (vegetable) waste by briquetting it, obtaining combined fuel briquettes and further use in small boilers.

2.2 Analysis of the raw material base of the Pavlodar region for agricultural and industrial waste

The sown area of agricultural crops in the Pavlodar region in 2023 amounted to 1332609.1 hectares. In the Pavlodar region, most (77.2 %) of the sown areas are devoted to the cultivation of cereals and oilseeds (900.4 and 179.5 hectares, respectively). The gross harvest of grains and legumes in 2021 for our region amounted to 10,052,492.7 centners, for oilseeds – 2,151,207 centners [37].

In accordance with statistical data in the Pavlodar region, the annual harvest of grains and legumes averages 492.8 thousand tons and more. If we talk about oilseeds, the harvesting of these crops over the past six years has averaged 133.5 thousand tons per year. Of this, 117.0 thousand tons are collected from sunflower seeds [33].

According to [33], in 2022, the harvest of grains and legumes in the region amounted to 958.056 thousand tons, oilseeds – 206.627 thousand tons. The significant part of the oilseeds are sunflower seeds (175.965 thousand tons). One can see a noticeable increase in the harvesting of these crops recently in the region. Harvesting of some types of agricultural crops in the Pavlodar region for 2022 is presented in table 2.3.

Table 2.3 – Harvesting of some types of agricultural crops in the Pavlodar region for 2022

Grain	Quantity in thousand tons
Wheat	660.885
Sunflower	175.965
Barley	117.295
Buckwheat	44.432
Oats	22.892
Millet	14.130
Corn	13.130
Lentils	4.103

Analyzing the harvest data in the Pavlodar region, we can conclude that the main part of the grain harvest is wheat. At the same time, Pavlodar region is in first place in the country in terms of the results of harvesting buckwheat and millet.

As mentioned above, the Republic of Kazakhstan is an industrialized state. Every year, about hundreds of thousands of tons of solid industrial waste are generated on our territory, which are poorly disposed of and are mainly stored in dumps near enterprises. As a result, there is an accumulation and migration of solid pollutants into the environment, which is due to the constant increase in waste generated and the low degree of their disposal.

According to [35], for 2022 the amount of emissions of solid pollutants amounted to 446.3 thousand tons. These include waste from the metallurgical, oil refining and energy industries.

On May 30, 2013, a presidential decree was adopted in Kazakhstan. The document was aimed at increasing the level of recycling and recycling of waste for recycling. Despite this legislative document, the share of industrial waste recycling in the country ranges from 3,302.0 to 10,730.1 thousand tons per year (minimum and maximum indicators are indicated).

Pavlodar region is the industrial center of Kazakhstan. The largest energy, metallurgical and petrochemical production facilities are concentrated here. Due to the high concentration of industrial production in the region, it accounts for the highest amount of industrial solid waste. For example, in 2022, 151.6 thousand tons of emissions of solid pollutants into the environment were recorded, which is 33.97 % of the total for the country.

According to experts, the volume of industrial waste (for example, coal and petcoke fines) can range from 30 to 70% of the main volume of production and processing [38]. According to UPNK-PV LLP (Pavlodar), up to 200 tons of coke dust is generated annually at the enterprise, which requires disposal.

2.3 Characteristics of raw materials used to produce fuel briquettes

In the presented study, plant waste from the agricultural sector and solid waste from industrial production were used as raw materials to obtain combined fuel briquettes. The waste was selected based on its availability and degree of prevalence in the Pavlodar region. For production and further study, the following raw materials for briquettes were used:

- sunflower husk;
- buckwheat husk;
- leaves;
- sunflower cake;
- coke dust.

As is known, agricultural crops (their waste) are characterized by a low content of ash, moisture and harmful compounds (sulfur and nitrogen).

Sunflower husks are a waste of oilseed production during the processing of sunflower seeds. The husks are separated when preparing the sunflower seeds to extract the oil during the hulling process. It consists of a large amount of cellulose, so it can be compared to sawdust, bark, buckwheat husks, pine or hazelnut shells. The physical structure of sunflower husk is homogeneous, bulk density ranges from 85 to 140 kg/m^3. Husks are easily crushed and pressed due to the oily component and lignin. The oily component in the husk ranges from 22.5 % to 50 % (depending on the sunflower variety). In its chemical composition, sunflower husk contains up to 34.17 % lignin and has a high yield of volatile substances from 68.77 to 83.6 % [24, 25]. The ash content of the husks is low, varying from 2.86 to 3 %. The moisture content of the husks is also satisfactory (from 4.5 to 10 % [39)]. Sunflower husks have a fairly high heat content (from 18.9 to 20 MJ/kg) [40]. From the point of view of environmental damage, burning sunflower husks does not pose a threat to the environment. The fact is that when burning husks, no more carbon dioxide is released than during the natural decomposition of wood, and a negligible amount of harmful emissions is generated. The ash remaining after burning sunflower husks is excellent for fertilizing plants. There are even special boilers that use sunflower husks as fuel.

Buckwheat husk is formed during the cleaning of buckwheat and is a waste product from this production. It consists of buckwheat flakes left after grain processing. Its structure is hard, dry and heterogeneous, has many air cavities, bulk density ranging from 160 to 195 kg/m^3. Buckwheat husk contains ash ranging from 1.5 to 2.3 %, moisture from 6.4 to 10.1 % [41]. The volatile yield for this material ranges from 73.86 to 74.4 % [42], the calorific value ranges from 17.19 to 18.4 MJ/kg. The internal structure of buckwheat husk consists of difficult-to-hydrolyze polysaccharides, including lignin in an amount of 24.8 to 28.2 %, the release of which occurs only when heated to temperatures above 160 °C and pressure. Thus, pressing buckwheat husks is associated with difficulties and requires heat exposure in order to activate the work of the binder – lignin.

Buckwheat hulls contain relatively few other binders, such as starch, for example, which are necessary in the production of briquettes.

To summarize, we can say that buckwheat hulls are more difficult to crush and briquet than sunflower hulls.

Fallen leaves, although not a waste of crop production, can nevertheless be used as raw materials for the production of fuel briquettes. They form in large numbers in urban areas in the autumn. Due to the lack of technologies for their disposal, most of the leaves rot or are burned in the open air, which causes damage to the environment.

This study used fallen poplar leaves collected from a park area near a higher education institution.

Fallen leaves have a fragile structure and low bulk density from 30 to 50 kg/m^3. Lignin is the most important component in leaves, giving them strength and stability. The percentage of lignin in fallen leaves can reach 50 [43]. In the process of briquetting deciduous mass, lignin serves as a “gluing” element that binds the components of the mixture into a homogeneous mass and increases the strength of the briquette.

Thus, fallen leaves are an easily accessible material for fuel briquettes and can be easily ground and pressed (due to their low bulk density and high lignin content).

Leaf moisture ranges from 8 % to 10 %, ash content, depending on temperature, can range from 11.62 % to 14.86 % [44]. The volatile yield of the leaves reaches 70 %, which indicates good reactivity as a fuel. The heat of combustion of dry leaves is quite high and ranges from 14 to 20 MJ/kg.

Sunflower cake, like sunflower husks, is a waste product, but it is formed in the process of obtaining oil from sunflower seeds. Sunflower cake is the compressed remains of sunflower seeds along with the peel. For this reason, sunflower cake has a high oil content. The percentage of oil content in the cake can reach 10 %. Due to the high proportion of oily substances in its composition, this material is very plastic and soft. It cannot withstand high pressing pressure. The bulk density of sunflower cake is in the range from 400 to 600 kg/m^3. The lignin content is low, on average this value is 4.9 % [45].

The moisture content in sunflower cake is low – 8.80 %, the ash content of the material ranges from 4.92 to 5.40 %. Sunflower cake, like other agricultural wastes, is characterized by a high volatile yield, the value of which varies from 60 to 70 %. Cake is also characterized by a high calorific value, which ranges from 20.47 to 23.98 MJ/kg [46].

After analyzing the considered plant waste, we can draw the following conclusion. The chemical composition of most agricultural and plant crops is similar to each other. It is worth noting that fallen leaves have a high ash content (from 11.62 to 14.86 %). This may be due to contamination of the raw materials themselves.

In this work, waste from oil calcination of coke – coke dust (and fines), as well as coal dust, which is formed in excess at enterprises when preparing coal for combustion, were used as raw materials of industrial origin. Coke dust, which is a product of the petrochemical industry, is obtained from the solid residue of petroleum refining (raw coke) into a continuous coke calcination unit at temperatures up to 1350 °C. Petroleum calcined coke differs from coke produced from coal in that it contains less ash (6.65 %) and sulfur, and also has a higher calorific value.

As a result, the resulting calcined coke has a low moisture content (3.06 %), high carbon concentration (87.48 %) and high heat content (from 26.87 kJ/kg to 29.84 kJ/kg). The yield of volatiles when compared with plant waste is quite small (9.81 %). It is comparable to the yield of volatile lean coals and anthracites (up to 13 %). In their pure form, coke dust and fines are rarely used for briquetting. but as a component for a fuel briquette it is of great value. This value is explained by the high carbon content (87.48 %) and low ash content (6.65 %).

On the other hand, fine dispersion, low moisture content, lack of internal binding components in the composition of coke dust and low density create difficulties in the formation of briquettes from pure raw materials. To solve these problems, it is proposed to combine coke dust with crop waste and fallen leaves.

The characteristics of the raw materials that were used to produce briquettes are presented in table 2.3.

Table 2.3 – Thermal characteristics of raw materials used to produce briquettes

Name of indicator (average value)	sunflower husk (0-3mm)	sunflower cake (0-2mm)	leaves (0-2mm)	buckwheat (3-6 mm)	coke dust UPNK-PV LLP
Total moisture in fuel operating condition, %	3,86	4,50	2-4	6,40	1,70-3,06
Ash content in the dry state of fuel, %	2,26	2,30	6,50-14,50	2,30	6,65
Yield of volatile substances on a dry, ash-free state of fuel, %	78,00	55,00	64,00	73,00	9,81
Lower calorific value, kJ/kg	19031,00	20407,00	21206,91	17000,00	26871,00

2.4 Production of fuel briquettes

2.4.1 In this study, plant waste (including fallen leaves) and industrial waste were used to produce combined fuel briquettes. The following vegetable wastes were used: buckwheat husks, fallen leaves, sunflower husks, sunflower cake. Industrial waste includes coke dust and fines remaining after the process of oil calcination of coke. Next, the components of the mixture for fuel briquettes and their ratio in the mixture were determined.

The choice of components for obtaining a combined fuel briquette was determined by a number of factors:

- the resulting fuel briquette must have high strength and density;
- lignin must be present in sufficient quantity in one of the components of the mixture. this will avoid adding additional binder and improve the adhesion between the mixture fractions. Otherwise, the resulting briquette will be extremely fragile.

The production of briquettes was carried out without the use of special binding components. Lignin contained in plant waste and released at high pressure, as well as oil in sunflower husks and cake, can be considered as a binder of natural origin. A sufficient lignin content in plant waste has a positive effect on the physical characteristics of the resulting briquettes, namely density and strength.

The quality of the resulting combined fuel briquettes depends on several parameters:

- quality of raw materials. Particularly important is the moisture content of the raw materials used. Humidity must be within the limits established by the standard [47]. High humidity (above 10%) and low humidity (less than 5 %) cause problems during the briquetting process;

- quantitative content of natural binders (lignin, resins, oils) in the mixture. The presence of this type of binder in the required quantity has a positive effect on the quality of the briquette in terms of mechanical strength;

- duration of pressing. The briquetting process takes a certain period of time. Applying pressure to the mixture for too long can cause cracks to appear on the surface. A short-term exposure under pressure will not be sufficient to form strong bonds between the particles of the mixture and obtain a durable fuel briquette. The optimal pressing time is 50 to 60 seconds.

The technology for manufacturing combined fuel briquettes from plant and industrial waste consists of the following processes:

1. Preparation of raw materials. Preparation of vegetable and coal dust consists of:

- in pre-drying at ambient temperature;

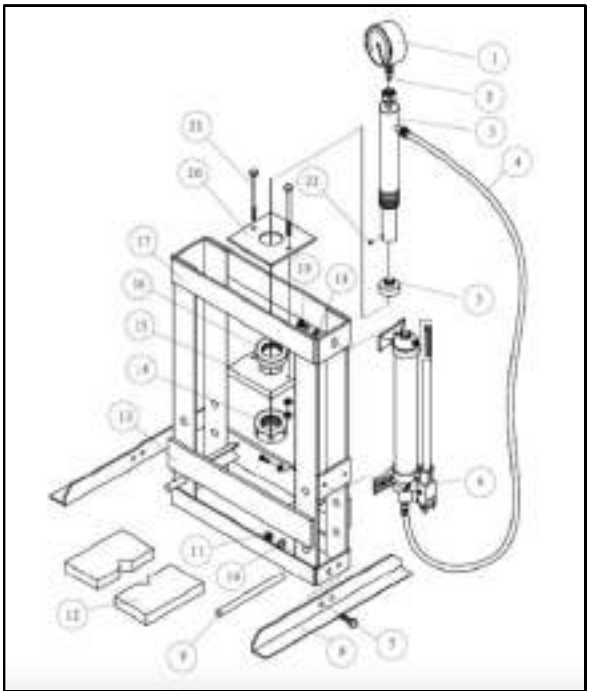
- in sifting and removing mechanical impurities from raw materials. For this purpose, sieves of different sizes are used. Cleaning is carried out in two stages: at the first stage, large fractions are removed, and at the second stage, fine particles are removed.

2. Grinding of raw materials. After cleaning the raw material, it must be crushed to a fraction size of less than 3 mm. This will improve the process of particle bonding.

3. Mixing the components of the mixture. Mixing of the selected raw materials occurs in a certain proportional ratio of the components. The weight of the mixture to obtain a briquette is 10 g. The prepared raw material mixture is thoroughly mixed and poured into the molding cylinder.

4. Production of fuel briquettes. The mixture is pressed using a hydraulic press with a pressure of 25 MPa. The mixture is pressed for one minute, then the finished briquette is removed from the molding cylinder by extrusion.

To produce combined fuel briquettes, a floor-mounted hydraulic press from Trommelberg (Germany) with a manual drive was used (figure 2.6). The press develops a maximum force of 30 tons.



1 – pressure gauge; 3 – cylinder; 4 – hydraulic hose; 5 – saddle; 6 – pump; 7 – bolt; 8 – support; 10 – washer; 11 – nut; 12 – frame; 14 – nut; 15 – plate; 16 – nut; 17 – frame; 20 – bolt; 21 – plate

Figure 2.6 – Diagram of a hydraulic press for briquetting

To determine the quality of binding of the mixture components and the strength of the briquettes at the output, various combinations of raw materials and their ratios in the mixture were studied. As a result, it was found that an increase in the composition of the mixture of buckwheat husks, regardless of the size of the fractional composition, leads to a decrease in the strength of the briquette, or its complete destruction. This factor is unacceptable; the fuel briquette must be dense and mechanically strong, capable of withstanding external physical influences during transportation and storage.

For the experimental study, a number of briquettes with different mixture composition ratios were produced by pressing, which included both industrial waste (coal and coke dust) and plant waste (buckwheat husks, large and small fractions of sunflower, leaves, cake).

The quality of the resulting combined fuel briquettes is significantly influenced by the fractional composition of the raw materials. In the course of analyzing the influence of the fractional composition of the briquette on its strength characteristics, the following was revealed:

- pressing pure coke dust is difficult due to the dry and fine structure of the raw material. The use of coke dust requires the selection of a second component with a sufficient content of moisture, oil or lignin in the composition;

- mixing two components containing increased oiliness results in a briquette with low strength (the briquette could not withstand the pressure, the briquette was destroyed under minor external influence);

- the content of dry leaves in the mixture has a positive effect on the result. Almost all briquettes with sufficient leaf content are characterized by high density and strength. The exception was briquettes, in which the content of sunflower cake significantly exceeded the content of leaves;

- mixing buckwheat husks of any fractional composition (fine and large) with coke dust is impossible without additional binding components, since both raw materials are characterized by increased dryness and a small amount of natural binder;

- an increased content of oily substances in the initial mixture negatively affects the quality of the fuel briquette. After pressing, the briquette retains its shape, but the briquette is destroyed even with a slight mechanical impact on it;

- the strength of briquettes is significantly influenced by the moisture content of the raw material and lignin. If both components of the mixture have high humidity, then the strength of the briquette decreases and it becomes more friable.

2.4.2 Analysis of the resulting combined briquettes from plant waste according to external characteristics (table 2.4).

To obtain fuel briquettes, the following combinations of raw materials in briquettes were selected:

- buckwheat husk (large fraction) and sunflower husk;
- buckwheat husk (fine fraction) and leaves;
- sunflower leaves and husks;
- sunflower husks (fine fraction) and coke breeze;
- sunflower cake and coke breeze;
- buckwheat husk (fine fraction) and coke breeze.

Briquettes were made in the following ratios of mixture components: 70:30, 60:40, 50:50, 40:60, 30:70, 20:80.

Briquettes made from buckwheat husks (large fraction) and sunflower have a dense and durable shape only when the content of one of the components of the mixture is greater than the content of the other component. For example, a briquette made from buckwheat husks (large fraction) and sunflower in a portion ratio of 70% to 30% and with a ratio of 30% to 70% have a more dense and durable structure. The briquette is slightly subject to destruction and does not stratify along the edges, unlike other ratios in a mixture of this type. However, in the first case, due to the main content of buckwheat husk in the mixture, the briquette is more susceptible to separation in the lower and upper parts, since buckwheat is poorly pressed.

Table 2.4 – Description of the external characteristics of briquettes made from vegetable waste

Sample	Photo	Description
1	2	3
Buckwheat husk (large fraction) and sunflower husk (70 %:30 %)		Dense, smooth edges without defects, under mechanical stress it begins to crumble.
Buckwheat husk (large fraction) and sunflower husk (60 %:40 %)		It is dense, but with a slight mechanical impact it begins to collapse, the edges are uneven, there are cracks.
Buckwheat husk (large fraction) and sunflower husk (50%:50%)		Durable, withstands mechanical stress, however, due to buckwheat on the edges, it is subject to slight delamination.
Buckwheat husk (large fraction) and sunflower husk (40 %:60 %)		The texture is loose, destroyed by mechanical stress.
Buckwheat husk (large fraction) and sunflower husk (30 %:70 %)		Durable, does not collapse under mechanical stress. The edges are smooth and do not delaminate.
Buckwheat husk (fine fraction) and leaves (30 %:70 %)		Very durable and dense, does not collapse under mechanical stress, the edges are even, and does not delaminate.
Buckwheat husk (fine fraction) and leaves (40 %:60 %)		Durable and dense, slightly loose, slightly susceptible to destruction, the edges are slightly flaky.

continuation of table 2.4

1	2	3
Buckwheat husk (fine fraction) and leaves (50 %:50 %)		Durable and dense, slightly susceptible to destruction, the edges are slightly flaky.
Buckwheat husk (fine fraction) and leaves (60 %:40 %)		Dense and durable, does not collapse under mechanical stress, the edges slightly delaminate.
Buckwheat husk (fine fraction) and leaves (70 %:30 %)		Very dense and durable, not subject to destruction under mechanical influence, the edges are smooth and do not delaminate.
Sunflower leaves and husks (30 %:70 %)		Dense and durable, slightly susceptible to destruction under mechanical influence, the edges are even, but slightly flaky.
Sunflower leaves and husks (40 %:60 %)		Dense, but destroyed by mechanical impact, the texture is loose.
Sunflower leaves and husks (50%:50%)		Dense, but under mechanical influence it is slightly destroyed, the texture is loose, the edges are even.
Sunflower leaves and husks (60 %:40 %)		Dense, but destroyed by mechanical impact, the texture is loose, the edges exfoliate.
Sunflower leaves and husks (70 %:30 %)		Durable and very dense, does not collapse under mechanical stress, the edges are even.

The oiliness of the sunflower husk plays a significant role in the production of briquettes from sunflower husks and buckwheat husks. The higher the oiliness of the sunflower husk, the more difficult the briquette formation process will be. The texture of such a briquette will be looser, which increases the risk of violating its integrity.

Briquettes made from buckwheat husks (fine fraction) and leaves have much greater density and strength in all ratios of components. Samples with a raw material ratio of 70 % to 30 % and 30 % to 70 % (buckwheat husk: leaves) have the best physical characteristics among the entire range of ratios considered.

Briquettes made from sunflower leaves and husks. The presence of crushed dry leaves in the mixture almost always (depending on the type of the second component) ensures the production of a dense and durable fuel briquette. The pressing process does not cause difficulties. The reason for the good result is the content of lignin in the leaves, which acts as a binder of natural origin. All samples made from sunflower leaves and husks have good characteristics. With an increase in the content of sunflower husks in the mixture, the briquette becomes looser and softer. An increase in husk content inevitably leads to a decrease in the strength characteristics of the briquette. The reason for this decrease is the high oiliness of sunflower husks. It was revealed that combined briquettes with a percentage of 30% husks and 70 % leaves have the best strength characteristics.

Briquettes were also made from a mixture of plant and industrial waste. The resulting fuel briquettes and their analysis are presented in table 2.5. Coke breeze and dust were used as raw materials of industrial origin. Buckwheat husks (of various fractions), as well as sunflower cake and sunflower husks were used as plant waste.

Table 2.5 – Briquettes from agricultural and industrial waste

Sample	Photo	Description
1	2	3
Sunflower husks (fine fraction) and coke breeze (30 % 70 %)		Destroys from minor mechanical impacts, does not hold its shape,
Sunflower husks (fine fraction) and coke breeze (40 %:60 %)		More dense, holds its shape, is destroyed by mechanical stress, the edges are not even, and crumbles.

continuation of table 2.5

1	2	3
Sunflower husks (fine fraction) and coke breeze (50 %:50 %)		More dense, holds its shape, is destroyed by mechanical stress, the edges are even
Sunflower husks (fine fraction) and coke breeze (60 %:40 %)		Dense and durable, not subject to destruction from mechanical influences, the edges are even, and does not delaminate.
Sunflower husks (fine fraction) and coke breeze (70 %:30 %)		Very dense and durable, not subject to destruction from mechanical stress, the edges are even, and does not delaminate.
Sunflower cake and coke breeze (70 %:30 %)		Dense, slightly loose texture, not subject to destruction from mechanical stress, smooth edges, does not delaminate.
Sunflower cake and coke breeze (60 %:40 %)		Dense and durable, the texture is slightly loose, is not subject to destruction from mechanical stress, the edges are even, and does not delaminate.
Sunflower cake and coke breeze (50 %:50 %)		Dense, not subject to destruction from mechanical influences, the edges are even, does not delaminate.
Sunflower cake and coke breeze (40 %:60 %)		Dense, destroyed by mechanical stress, the edges are not even, slightly crumbles.
Sunflower cake and coke breeze (30 %:70 %)		Does not hold its shape and is destroyed by light mechanical influences.

continuation of table 2.5

1	2	3
Buckwheat husk (fine fraction) and coke breeze (30 %:70 %)		It is destroyed by small mechanical influences, the edges are not even.
Buckwheat husk (fine fraction) and coke breeze (40 %:60 %)		Keeps its shape, is destroyed by minor mechanical influences, the edges are not even.
Buckwheat husk (fine fraction) and coke breeze (50 %:50 %)		Dense, it collapses under mechanical influence, the edges are even, slightly delaminates, cracks from the pressure of the press are noticeable.
Buckwheat husk (fine fraction) and coke breeze (60 %:40 %)		Dense, it collapses under mechanical stress, the edges are even, slightly flaky in the upper part.
Buckwheat husk (fine fraction) and coke breeze (70 %:30 %)		Dense, it collapses under mechanical influence, the edges are even, slightly delaminates, cracks from the pressure of the press are noticeable.

Some of the manufactured fuel briquettes include waste from oil calcination of coke – coke dust. Coke dust is a dry, free-flowing, finely dispersed substance that is difficult to compress. Low humidity in coke breeze is caused by the peculiarities of the technological process during which it is produced. This process is characterized by a very high temperature regime. To obtain a durable briquette, it is better to mix coke dust with raw materials that contain sufficient moisture content and a natural binder.

During a visual inspection of the resulting briquettes of this type, it is clear that with an increase in the content of coke dust in the composition, the briquette ceases to hold its shape and crumbles even from minor mechanical influences.

Among the combined fuel briquettes containing coke dust and sunflower husk (large fraction) in their composition, samples with a percentage of raw materials of 40 %:60 % and 30 %:70 % (coke breeze: sunflower husk) have the best strength characteristics. Briquettes with this mixture ratio are quite strong and dense. The oily component of sunflower husk compensates for the dryness of coke dust and the resulting briquette is very dense, without destruction along the edges.

Briquettes made from coke dust and sunflower cake have good strength characteristics. They hold their shape well, with the exception of samples with a predominant content of coke dust. Due to the high degree of oiliness, particles of cake and coke dust adhere well to each other, and the briquettes are perfectly compressed.

Samples made from fine buckwheat husks and coke dust crumble despite the fact that they hold their shape and look dense in appearance. Low adhesion is explained by the fact that buckwheat husk does not contain a “natural” binder and is too dry. In this regard, difficulties are created in pressing this mixture. The most durable briquette was obtained with a mixture percentage of 60 %:40 % (buckwheat husk: coke breeze).

2.5 Methodology for determining the thermal characteristics of fuel briquettes

In order to determine the most promising combined briquettes from a fuel point of view, more in-depth research is needed. The thermal characteristics of each type of briquettes were experimentally determined.

The humidity, ash content, volatile yield, density, strength and calorific value of the resulting briquettes were studied. The experimental data were carefully analyzed.

2.5.1 Determination of moisture content of briquettes

As you know, humidity is one of the most important characteristics of any fuel. Increased moisture content in fuel negatively affects the combustion process, reducing its heat release. For briquetted fuel, humidity is also important from the point of view of strength properties. High humidity leads to damage to the integrity of the fuel briquette.

The moisture content in fuel briquettes was determined in accordance with [48]. The mass fraction of moisture content in the sample was determined based on the initial and final weight after heating it in the oven.

The percentage of moisture in the sample was calculated using the following formula

$$W_a = \frac{m_2 - m_3}{m_2 - m_1} \cdot 100, \% , \tag{2.1}$$

where m_1 – empty crucible weight, g;

m_2 – weight of the crucible with the sample before drying in the furnace, g;

m_3 – crucible weight after drying in the furnace, g.

2.5.2 Determination of ash content of briquettes

The ash content of a fuel briquette is the percentage of non-combustible mineral residue in the sample. High ash content negatively affects the heat of combustion and worsens the combustion process. In addition, the load on the ash and slag removal system increases. The ash content of the briquettes considered was determined in accordance with the method described in [49]. During the study, a sample of fuel was calcined in a muffle furnace at a temperature of 815±10 °C.

The proportion of ash in fuel briquettes was determined by the following formula

$$A_a = \frac{m_2 - m_3}{m_2 - m_1} \cdot 100, \%, \qquad (2.2)$$

where m_1 – empty crucible weight, g;

m_2 –weight of the crucible with a sample before calcination in the furnace, g;

m_3 – rucible weight after calcination in the furnace, g

2.5.3 Determination of volatile matter yield

The yield of volatile substances was determined according to the method presented in [50]. To determine the yield of volatile substances, the sample was heated without air access at a temperature of 900±10 °C. The volatile yield was determined using the following formula

$$V^d = \left[\frac{100\,(m_2 - m_3)}{m_2 - m_1} - W^a\right]\left(\frac{100}{100 - W^a}\right), \% \qquad (2.3)$$

where m_1 – empty crucible weight, g;

m_2 –weight of the crucible with a sample before calcination in the furnace, g;

m_3 – rucible weight after calcination in the furnace, g

W^a – mass fraction of moisture in the sample, %.

2.5.4 Determination of density

The briquette density was determined in accordance with [51]. To calculate the density, it is necessary to determine the height and mass of the fuel briquette. The measurement is made using calipers and laboratory scales. Density was founded by the next formula

$$\rho = \frac{m}{V}, \qquad (2.4)$$

where m – mass of the briquette, g;

V – briquette volume, m^3.

The briquette is cylindrical in shape, the volume is calculated by the formula

$$V = \frac{1}{4}\pi \cdot d^2 \cdot h\,, \qquad (2.5)$$

where d – diameter of the cylinder, m;
h – briquette height, m.

2.5.5 Determination of the mechanical strength of briquettes

The strength of fuel briquettes was determined using the method presented in [52]. Mechanical impact was applied to the briquettes. The briquettes were loaded into a container with an opening bottom and dropped from a given height (1.5 m). Next, the mass with intact and damaged briquettes is unloaded and weighed.

The strength of the samples under study is determined by the deviation of the final weight of the briquettes from the initial weight of the briquettes

$$DU = \frac{m_A}{m_E} \cdot 100\,, \%\,, \qquad (2.6)$$

where m_A – mass of briquettes obtained as a result of the test, g;
m_E – mass of briquettes before testing, g.

2.5.6 Determination of the calorific value of briquettes

Data on the lower calorific value of briquettes were obtained experimentally at the Institute of Chemistry and Coal (Astana).

Kazakhstan has a large amount of industrial and organic waste. The most developed crop production sector is in Akmola, North Kazakhstan, Kostanay, Almaty and Pavlodar regions. On the territory of the Pavlodar region, wheat, buckwheat, oats and millet are grown, as well as oilseeds, most of which are sunflower seeds. The largest share of industrial waste also occurs in the Pavlodar region.

The developed technology for producing combined fuel briquettes makes it possible to obtain mechanically strong and dense fuel briquettes without the use of binding components.

The highest density is typical for briquettes with a high content of sunflower leaves and husks. The leaves contain lignin, which becomes pliable when subjected to pressure and acts as a natural binder. Sunflower husks contain oily substances in quantities sufficient to bind fractions.

Buckwheat husks are unsuitable as the main raw material for briquettes. The reason is the very dry structure and the absence of a natural binder in the raw material. Buckwheat husks of large fraction bind well to sunflower husks if the proportion of buckwheat content is no more than 30% in the total mass. The high oil content in sunflower cake has a bad effect on the quality of briquettes. The briquette crumbles under even slight mechanical stress. The optimal content of cake is 30% in the case of producing briquettes only from organic waste.

Mixing sunflower cake with coke dust has a positive effect on the final product. Thanks to the oily component, good binding occurs. It is not recommended to exceed the cake content above 50%.

2.6 Determination of the elemental composition of biochar briquettes

To study the elemental composition, biochar briquettes from industrial and plant waste were selected. The elemental composition and lower calorific value of briquettes were determined. Coal dust from the Shubarkul and Maikubensky coal mines was taken as industrial waste. Fallen leaves, buckwheat husks, sunflower husks and sunflower cake were taken as plant raw materials. The characteristics of the feedstock for combined biochar briquettes are presented in table 2.6.

Table 2.6 – Characteristics of coal dust and plant waste

Raw materials	Compound, %							Lower calorific value $Q_н^р$, MJ/kg	Yield of volatile substances $V_г$, %
	$W^р$	$A^р$	$S_л^р$	$C^р$	$H^р$	$N^р$	$O^р$		
Industrial waste									
Coal dust (Shubarkol)	14,50	9,00	0,43	58,84	4,20	1,23	11,80	25,06	44,50
Coal dust (Maicuben)	18,00	22,00	0,40	43,80	3,06	0,60	12,14	18,76	42,10
Plant waste									
Leaves	3,00	4,50	0,10	43,10	6,50	2,00	40,80	21,21	64,00
Buckwheat husk	6,40	2,30	0,25	44,12	5,30	1,50	40,13	17,00	73,00
Sunflower husk	3,86	2,10	0,27	45,06	6,86	1,02	40,83	19,03	78,00
Sunflower cake	4,50	2,30	0,08	44,52	4,20	2,80	41,60	20,41	55,00

The following mixture compositions were selected as objects of study:
- coal dust (Shubarkol): sunflower husks;
- coal dust (Shubarkol): buckwheat husk;
- coal dust (Shubarkol): leaves;
- coal dust (Shubarkol): sunflower cake;
- coal dust (Maikuben): sunflower husks;

- coal dust (Maikuben): buckwheat husk;
- coal dust (Maikuben): leaves;
- coal dust (Maikuben): sunflower cake.

The following options for combining coal dust with plant waste were considered; 20:80%, 30:70%, 40:60%, 50:50%, 60:40%, 70:30%, 80:20%.

A calculation method was chosen to determine the elemental composition of bio-coal briquettes. During the calculation, the percentage content of each of the mixture components was taken into account. As a result of the calculation, the elemental compositions of the briquettes were obtained.

The net heating value of biochar briquettes was calculated using the formula, MJ/kg

$$Q_{н}^{р} = 338C^{р} + 1025H^{р} + 108{,}5(O^{р} - S_{л}^{р}) - 25W^{р},$$

where $C^{р}$, $H^{р}$, $O^{р}$, $S_{л}^{р}$, $W^{р}$ – content of elements in the working mass of fuel, %.

In the course of the calculations, the elementary composition of each of the briquettes was determined. Based on the elemental composition, the lower heating values of bio-coal briquettes were calculated. The results are presented in tables 2.7 and 2.8.

Table 2.7 presents the results of the analysis of briquettes from plant waste mixed with coal dust from the Shubarkol deposit.

Table 2.7 – Elemental composition and calorific value of briquettes from plant waste mixed with coal dust from the Shubarkol deposit

Ratio	PW	Compound, %							Lower calorific value $Q_{н}^{р}$, MJ/kg	Yield of volatile substances $V_{г}$, %
		$W^{р}$	$A^{р}$	$S^{р}$	$C^{р}$	$H^{р}$	$N^{р}$	$O^{р}$		
80:20	SH	12,37	7,62	0,39	56,08	4,73	1,18	17,60	22,56	51,20
	BH	12,88	7,66	0,39	55,89	4,42	1,28	17,46	22,16	50,20
	L	12,20	8,10	0,36	55,69	4,66	1,38	17,60	23,00	48,40
	SC	12,50	7,66	0,36	55,97	4,20	1,54	17,76	22,84	46,60
70:30	SH	11,30	6,93	0,38	54,70	4,99	1,16	20,50	22,12	54,55
	BH	12,07	6,99	0,37	54,42	4,53	1,31	20,29	21,51	53,05
	L	11,00	7,65	0,33	54,11	4,89	1,46	20,50	22,77	50,35
	SC	11,50	6,99	0,32	54,54	4,20	1,70	20,74	22,53	47,65

continuation of table 2.7

60:40	SH	10,24	6,24	0,36	53,32	5,26	1,14	23,41	21,68	57,90
	BH	11,26	6,32	0,35	52,95	4,64	1,33	23,13	20,87	55,90
	L	9,90	7,20	0,29	52,54	5,12	1,53	23,40	22,55	52,30
	SC	10,50	6,32	0,29	53,11	4,20	1,85	23,72	22,23	48,70
50:50	SH	9,18	5,55	0,35	51,95	5,53	1,12	26,31	21,24	61,25
	BH	10,45	5,65	0,34	51,48	4,75	1,36	25,96	20,22	58,75
	L	8,75	6,75	0,26	50,97	5,35	1,61	26,30	22,33	54,25
	SC	9,50	5,65	0,25	51,68	4,20	2,01	26,7	21,93	49,75
40:60	SH	8,11	4,86	0,33	50,57	5,79	1,10	29,21	20,79	64,60
	BH	9,64	4,98	0,32	50,00	4,86	1,39	28,79	19,58	61,60
	L	7,60	6,30	0,23	49,39	5,58	1,69	29,20	22,10	56,20
	SC	8,50	4,98	0,22	50,24	4,20	2,17	29,68	21,62	50,80
30:70	SH	7,05	4,17	0,31	49,19	6,06	1,08	32,12	20,35	67,95
	BH	8,83	4,31	0,30	48,53	4,97	1,41	31,63	18,94	64,45
	L	6,45	5,85	0,19	47,82	5,81	1,76	32,10	21,88	58,15
	SC	7,50	4,31	0,18	48,81	4,20	2,32	32,66	21,32	51,85
20:80	SH	5,98	3,48	0,30	47,81	6,32	1,06	35,02	19,91	71,30
	BH	8,02	3,64	0,28	47,06	5,08	1,44	34,46	18,29	67,30
	L	5,30	5,40	0,16	46,24	6,04	1,84	35,00	21,65	60,10
	SC	6,50	3,64	0,15	47,38	4,20	2,48	35,64	21,01	52,90

* SH – sunflower husk, BH – buckwheat husk, L – leaves, SC – sunflower cake.

Analysis of the data in Table 2.7 showed that the highest carbon content (from 55.97 % to 56.08 %) was found in briquettes made from 80 % coal dust and 20 % plant waste. Briquettes containing sunflower husks and cake have the highest carbon content (56.08 %). The lowest carbon content (46.24 %) was found in briquettes of 20 % buckwheat husk and 80 % coal dust. This type of briquettes contains a large number of internal ballast elements (oxygen, nitrogen).

Analysis of the moisture content in the presented briquettes allows us to make the following statements. The maximum moisture concentration (12.88 %) was observed in briquettes containing buckwheat husks in a ratio of 80 % coal:20 % husks. The minimum level of humidity (5.30 %) was observed for briquettes made from 20 % coal and 80 % leaves.

The yield of volatile substances per combustible mass is highest in samples with a lower content of coal dust. This is explained by the high level of volatile substances released from plant materials. The highest yields of volatile substances (from 67.30 % to 71.30 %) were found in briquettes containing sunflower husks and buckwheat husks.

High values of the lower calorific value were shown by all briquettes using sunflower cake and husk (figure 2.7).

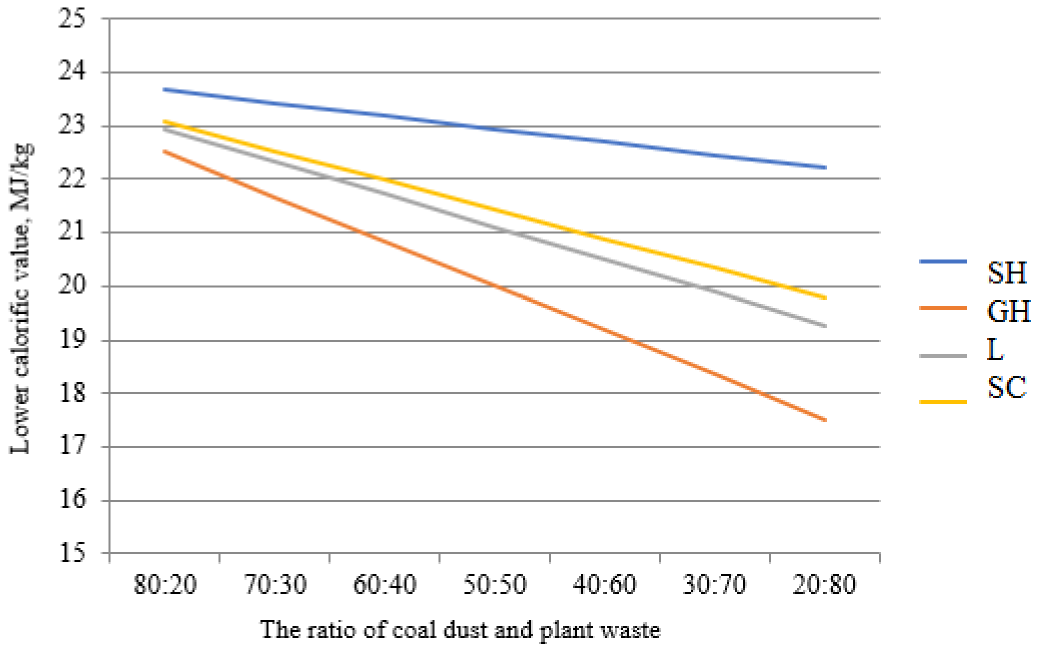


Figure 2.7 – Lower calorific value of briquettes made from plant waste and coal dust (Shubarkul)

Let us consider the nature of the change in the lower calorific value of briquettes depending on the ratio between coal dust and plant waste. Let us note the general trend of a decrease in the calorific value of these briquettes with a decrease in the percentage of coal dust. The highest values of lower calorific value were found for briquettes with sunflower husks (from 23.67 MJ/kg to 22.20 MJ/kg) and sunflower cake (from 23.07 MJ/kg to 19.8 MJ/kg). Briquettes with leaves (from 22.94 MJ/kg to 19.28 MJ/kg) and buckwheat husks (from 22.50 MJ/kg to 17.52 MJ/kg) have lower values of lower calorific value.

Table 2.8 summarizes the results of calculating the elemental composition of briquettes from plant waste and coal dust from the Maikubensky deposit.

In accordance with table 2.8, it was determined that the highest carbon content (from 43.24 % to 44.80 %) is typical for briquettes in a ratio of 20:80 (plant waste: coal dust). The carbon content predominates in briquettes made from sunflower husks and sunflower cake. The lowest carbon content (43.24 %) was found in briquettes made from leaves in a ratio with coal (20:80).

The dominance of such ballast substances as nitrogen and oxygen is also typical for briquettes made from buckwheat husks.

Table 2.8 – Elemental composition and calorific value of briquettes from plant waste mixed with coal dust from the Maikuben deposit

Ratio	PW	Compound, %							Lower calorific value $Q_н^р$, MJ/kg	Yield of volatile substances $V_г$, %
		W^p	A^p	S^p	C^p	H^p	N^p	O^p		
80:20	SH	15,17	18,02	0,37	44,05	3,82	0,68	17,87	17,50	49,28
	BH	15,68	18,06	0,37	43,86	3,50	0,78	17,73	17,09	48,28
	L	15,00	18,50	0,34	43,66	3,74	0,88	17,87	17,93	46,48
	SC	15,30	18,06	0,33	43,94	3,28	1,04	18,03	17,77	44,68
70:30	SH	13,75	16,03	0,36	44,17	4,20	0,72	20,74	17,69	52,87
	BH	14,52	16,09	0,35	43,89	3,73	0,87	20,53	17,08	51,37
	L	13,50	16,75	0,31	43,59	4,09	1,02	20,73	18,34	48,67
	SC	13,95	16,09	0,30	44,01	3,40	1,26	20,97	18,10	45,97
60:40	SH	12,34	14,04	0,34	44,30	4,58	0,76	23,61	17,88	56,46
	BH	13,36	14,12	0,34	43,92	3,95	0,96	23,33	17,07	54,46
	L	12,00	15,00	0,28	43,52	4,43	1,16	23,60	18,75	50,86
	SC	12,60	14,12	0,27	44,08	3,51	1,48	23,92	18,43	47,26
50:50	SH	10,93	12,05	0,33	44,43	4,96	0,81	26,48	18,07	60,05
	BH	12,20	12,15	0,32	43,96	4,18	1,05	26,13	17,06	57,55
	L	10,50	13,25	0,25	43,45	4,78	1,30	26,47	19,16	53,05
	SC	11,25	12,15	0,24	44,16	3,63	1,70	26,87	18,76	48,55
40:60	SH	9,51	10,06	0,32	44,55	5,34	0,85	29,35	18,26	63,64
	BH	11,04	10,18	0,31	43,99	4,40	1,14	28,93	17,04	60,64
	L	9,00	11,50	0,22	43,38	5,12	1,44	29,33	19,57	55,24
	SC	9,90	10,18	0,20	44,23	3,74	1,92	29,81	19,09	49,84
30:70	SH	8,10	8,07	0,30	44,68	5,72	0,89	32,22	18,45	67,23
	BH	9,88	8,21	0,29	44,02	4,62	1,23	31,73	17,03	63,73
	L	7,50	9,75	0,19	43,31	5,46	1,58	32,20	19,98	57,43
	SC	8,55	8,21	0,17	44,30	3,85	2,14	32,76	19,42	51,13
20:80	SH	6,688	6,08	0,29	44,80	6,1	0,93	35,09	18,64	70,82
	BH	8,72	6,24	0,28	44,05	4,85	1,32	34,53	17,02	66,82
	L	6,00	8,00	0,16	43,24	5,81	1,72	35,06	20,39	59,62
	SC	8,55	8,21	0,17	44,30	3,85	2,14	32,76	19,42	51,13

* SH – sunflower husk, BH – buckwheat husk, L – leaves, SC – sunflower cake.

The maximum moisture content (15.68 %) was found in fuel briquettes made from 80 % coal dust and 20 % buckwheat hulls. The minimum moisture content (6.00 %) was found in fuel briquettes made from 20 % coal dust and 80 % leaves. The yield of volatile substances per combustible mass is greatest in samples with a lower content of coal dust. The highest yields of volatile substances are characteristic of biochar briquettes using 80 % sunflower husks (70.82 %) and in briquettes with

80 % buckwheat husks 20:80 (66.82 %). This is explained by the high level of volatile emissions from plant waste.

High values of lower calorific value were detected in samples using sunflower cake and husk, regardless of the ratio of waste (figure 2.8).

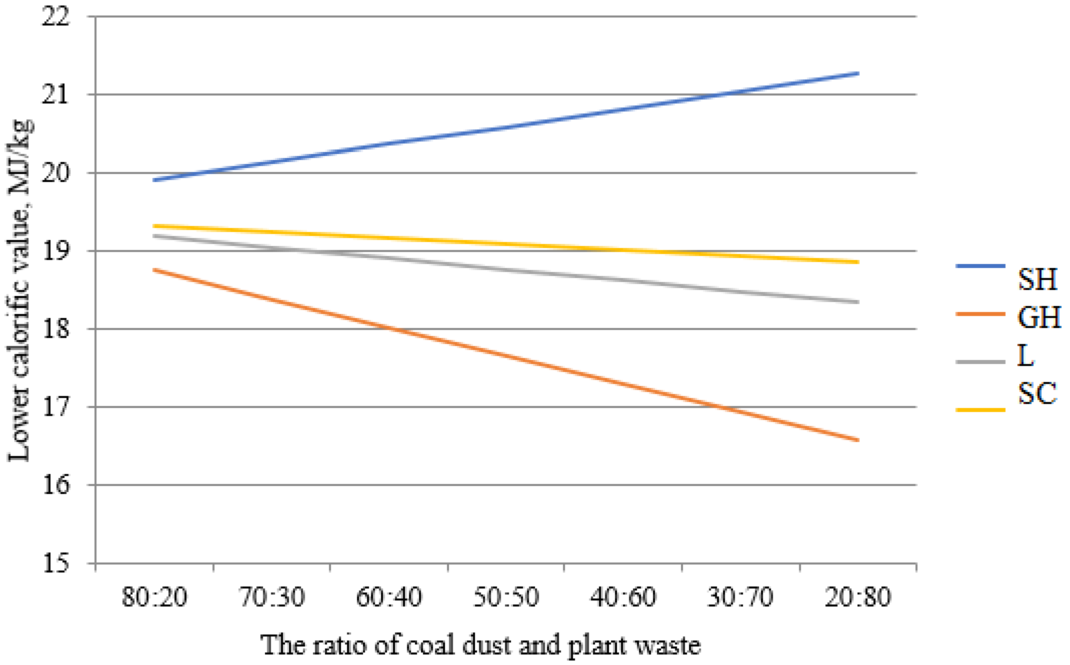


Figure 2.8 – Lower calorific value of briquettes made from plant waste and coal dust from the Maikubensky deposit

Analyzing the graph, we can observe an increase in the value of the lower calorific value with a decrease in the content of coal dust in samples containing sunflower husks (from 19.92 MJ/kg to 21.27 MJ/kg). For other types of briquettes, as the content of coal dust decreases, the lower calorific value decreases.

To check the adequacy of the data obtained by the calculation method, we will compare them with the data determined experimentally at the Institute of Chemistry and Coal (Astana). The test results are presented in table 2.9.

Table 2.9 – Results of comparative analysis

Briquette type	Heat of combustion, MJ/kg (calculation method)	Heat of combustion, MJ/kg (experimental method)	Percentage of discrepancy, %
Л:УШ (50 %:50 %)	21,11	20,99	0,53
ЛП:УШ (50 %:50%)	22,94	23,77	3,48
ЛП:УШ (80 %:20 %)	22,20	23,24	4,45
Л:УМ (50 %:50 %)	18,76	18,71	0,29

*УШ – уголь (Шубаркуль), УМ – уголь (Майкубень)

The percentage of discrepancy does not exceed 5%. Consequently, the calculation method for determining the heat of combustion of briquettes based on its elemental composition is correct, and the data obtained are adequate.

The most effective in terms of calorific value are considered to be biochar briquettes in the ratio of 80:20 Shubarkol and 20:80 Maikuben samples based on sunflower husks and cake. The most environmentally friendly, according to the indicators of the component composition, are samples containing one fifth of plant waste (due to the lower content of sulfur and nitrogen in the feedstock).

3 Analysis of the thermal characteristics of fuel briquettes from plant and industrial waste

3.1 Results of research on briquettes made from plant waste

The experimental studies were carried out in accordance with the methods [48 – 52] described in Chapter 2. The experimental study involved briquettes consisting of agricultural waste and briquettes made from plant and industrial waste.

Briquettes with the following component ratios were selected for the study: 30%:70%, 40%:60%, 50%:50%, 60%:40% and 70%:30%. This choice will allow you to track changes in the thermal characteristics of briquettes when the percentage of raw materials changes.

The obtained data on density, strength, humidity, ash, volatile yield and calorific value of briquettes from agricultural waste are presented in table 3.1.

Table 3.1 – Results of experimental studies of briquettes from agricultural waste

№	Mixture ratio, %:%	Density, kg/m^3	Strength, %	Humidity, %	Ash content, %	Volatile yield, %	Heat combustion, kJ/kg
1	Buckwheat husk (large fraction): sunflower husk						
	30:70	1228,35	79,92	4,50	3,65	81,27	18461,7
	40:60	1211,11	76,40	4,87	3,50	81,15	18138,6
	50:50	1056,13	73,20	5,13	3,40	79,77	18015,5
	60:40	844,64	69,05	5,3	3,30	77,60	17812,4
	70:30	789,58	66,48	5,50	3,00	76,20	17509,3
2	Buckwheat husk (fine fraction): leaves						
	30:70	1252,93	90,78	4,16	5,40	59,16	19844,2
	40:60	1236,77	88,56	4,50	5,00	60,21	19323,6
	50:50	1202,23	85,37	4,80	4,60	62,73	19103
	60:40	1179,58	82,49	5,00	4,00	65,26	18582,4
	70:30	1067,02	80,54	5,40	3,86	67,15	18241,8
3	Leaves: sunflower husk						
	30:70	1038,92	81,75	3,62	3,50	73,30	19583,5
	40:60	1050,53	82,89	3,59	4,00	73,06	19931
	50:50	1103,54	83,03	3,50	4,43	70,98	20168,5
	60:40	1290,00	86,05	3,48	4,82	63,73	20306
	70:30	1358,81	91,80	3,39	5,23	62,30	20553,5

3.1.1 Results for briquette density

The main factor determining the mechanical strength, water resistance and calorie content of a briquette is its density. The denser the briquette, the higher its quality indicators. Briquettes with high density hold their shape better, are less subject to deformation, and absorb moisture less well. Thus, the higher the density of the briquette, the more resistant it is to destructive influences.

Analysis of the data in Table 3.1 showed that the maximum density (1358.81 kg/m^3) has a briquette made of 70 % leaves and 30 % sunflower husks. It was found that all briquettes containing leaves have a fairly high density. This is due to the good pressing of the leaves due to their lignin content.

The situation is different with briquettes made from buckwheat husks (regardless of the size of the fractions) and sunflower. These briquettes are very fragile. The two samples have a minimum density of 789.5 kg/m^3 (70%:30%) and 844.6 kg/m^3 (60%:40%). The density of the remaining briquettes exceeds 1000 kg/m^3 and is good.

It has been established that with an increase in the content of buckwheat husks, briquettes are less susceptible to pressing. They have low density and are easily destroyed. This is due to the dry, dense and uneven structure of buckwheat. With a higher content of oily crops in the mixture, the briquette has a soft and loose structure. Briquettes are easily subject to destruction under mechanical stress. Therefore, in order to obtain a durable briquette, it is extremely important that the raw materials used are compatible with each other.

Let us consider on the graphs (figures 3.1–3.4) the change in the density of briquettes from buckwheat and sunflower husks, briquettes from buckwheat husks and leaves, briquettes from leaves and sunflower husks, depending on the percentage of components.

The dependence (figure 3.1) indicates a decrease in the density of a briquette made from buckwheat husks (large fraction) and sunflower husks with a decrease in sunflower husks in its composition.

Approximation of this dependence showed that it has a polynomial character

$$y = -9.439 \cdot x^2 - 67.765 \cdot x + 1333.1. \qquad (3.1)$$

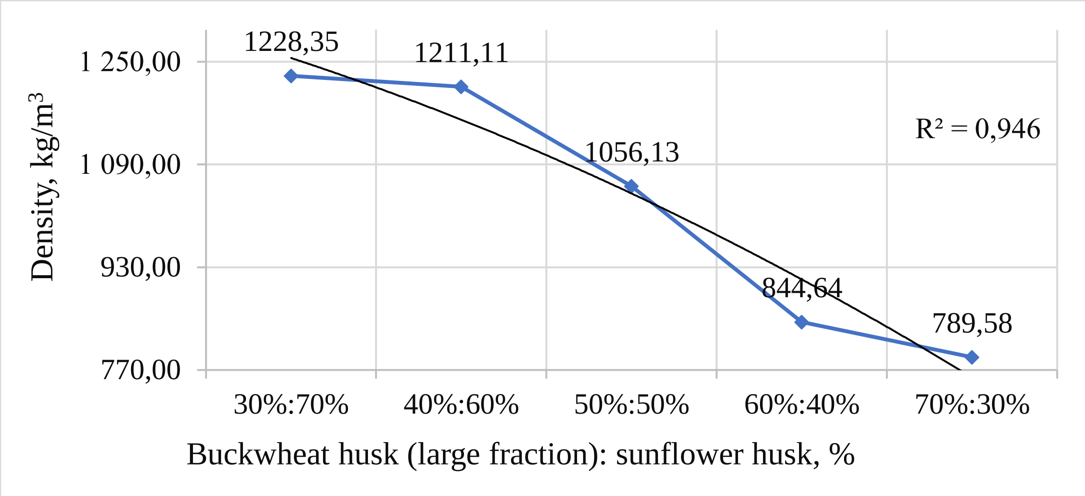


Figure 3.1 – Density of briquettes made from buckwheat husks (large fraction) and sunflower

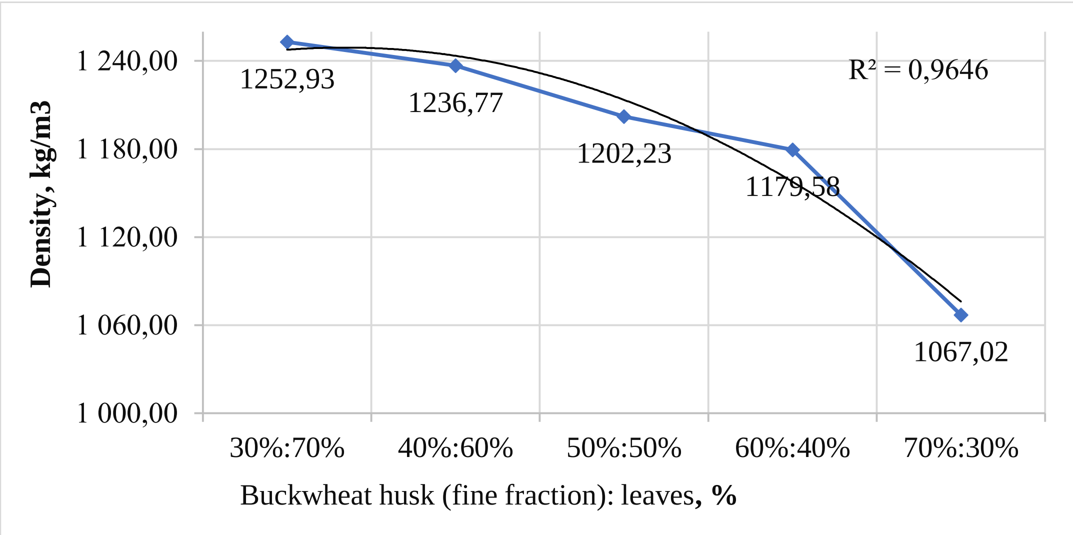


Figure 3.2 – Density of briquettes made from buckwheat husks (fine fraction) and leaves

Analysis of the relationship in figure 3.2 shows that with a decrease in leaves in the mixture, the density of the briquette from buckwheat husks (fine fraction) and leaves decreases. Approximation of the obtained dependence showed that it has a polynomial character

$$y = -12.922 \cdot x^2 + 34.632 \cdot x + 1226. \quad (3.2)$$

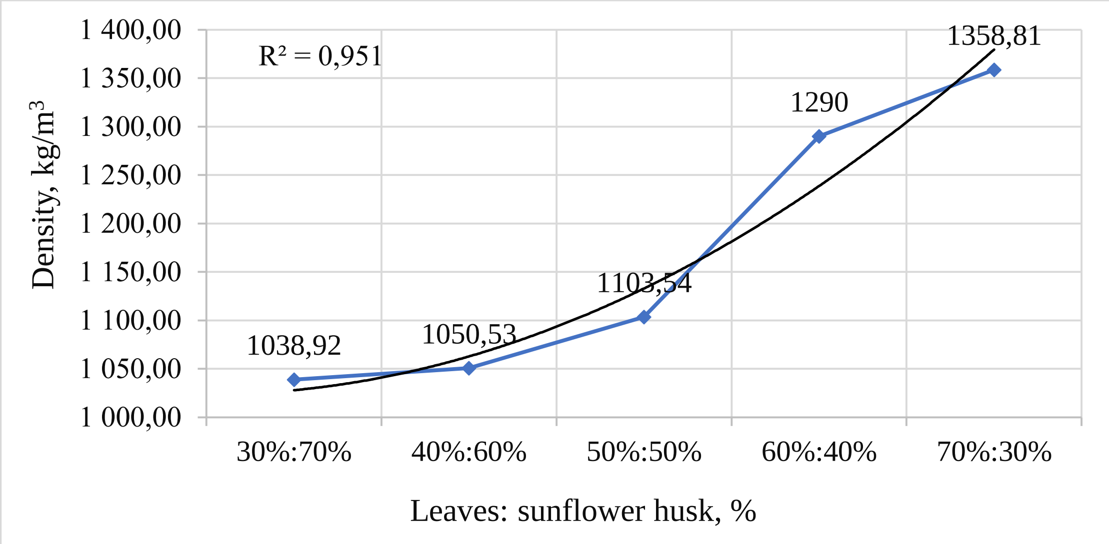


Figure 3.3 – Density of briquettes made from sunflower leaves and husks

The data presented in figure 3.3 show an increase in the density of a briquette of sunflower leaves and husks with an increase in leaves in its composition. The resulting dependence is polynomial in nature

$$y = 17.704 \cdot x^2 - 18.296 \cdot x + 1028.5. \quad (3.3)$$

Let us consider the nature of the change in density as a function of the ratio between the components in the briquettes studied (figure 3.4).

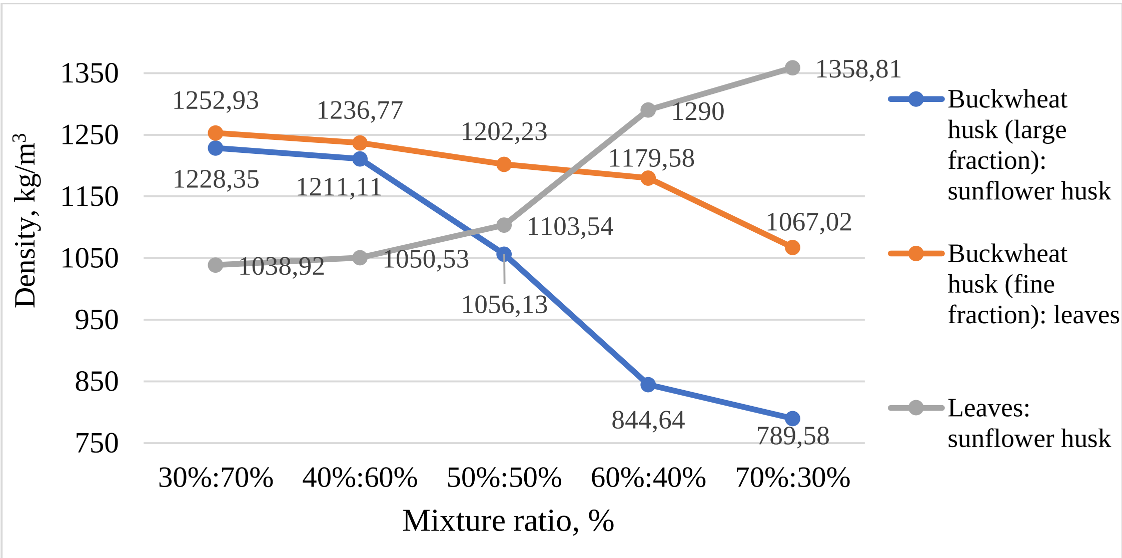


Figure 3.4 – Summary diagram of the dependence of briquette density on the ratio of components in the mixture

Analysis of figure 3.4 showed that briquettes containing leaves have the highest density. This is due to the lignin content in the leaves. An increase in the proportion of leaves in the briquette composition leads to an increase in its density. An increase in the content of buckwheat husk in a briquette leads to a decrease in its density, complicates the pressing process, and the resulting briquette is loose and easily subject to destruction.

3.1.2 Results on briquette strength

Strength is the most important characteristic of fuel briquettes. It reflects the suitability of briquettes for transportation and further use.

Analysis of the data in table 3.1 showed that the maximum strength value (91.80 %) is found in a briquette with 70 % leaves and 30 % sunflower husks. It is worth noting that all briquettes containing leaves have high strength characteristics.

Briquettes consisting of buckwheat and sunflower husks have low strength (66.48 % – 69.05 %). Briquettes with a percentage ratio of 30%:70% have the maximum strength in this series. Thanks to the oiliness of sunflower husks, binding of the mixture during the pressing process proceeds successfully.

In the process of manufacturing these briquettes, it was found that most briquettes have weakly or strongly expressed stratification along the edges (with the exception of briquettes with a large content of leaves). This is not a good sign, since these places are the most vulnerable.

Let's look at the graphs (figures 3.5 – 3.8) for changes in the strength of briquettes made from buckwheat and sunflower husks, buckwheat husks and leaves, leaves and sunflower husks, depending on the percentage of components.

Analysis of the dependence shown in figure 3.5 indicates a decrease in the strength of a briquette made from buckwheat husks (large fraction) and sunflower husks with a decrease in sunflower husks in its composition.

Approximation of this dependence showed that it is linear

$$y = -3.423 \cdot x + 83.279. \tag{3.4}$$

You can see in Figure 3.6 a decrease in the strength of a briquette made from buckwheat husks (fine fraction) and leaves with a decrease in leaves in its composition.

Approximation of this dependence showed that it is linear

$$y = -2.655 \cdot x + 93.513. \tag{3.5}$$

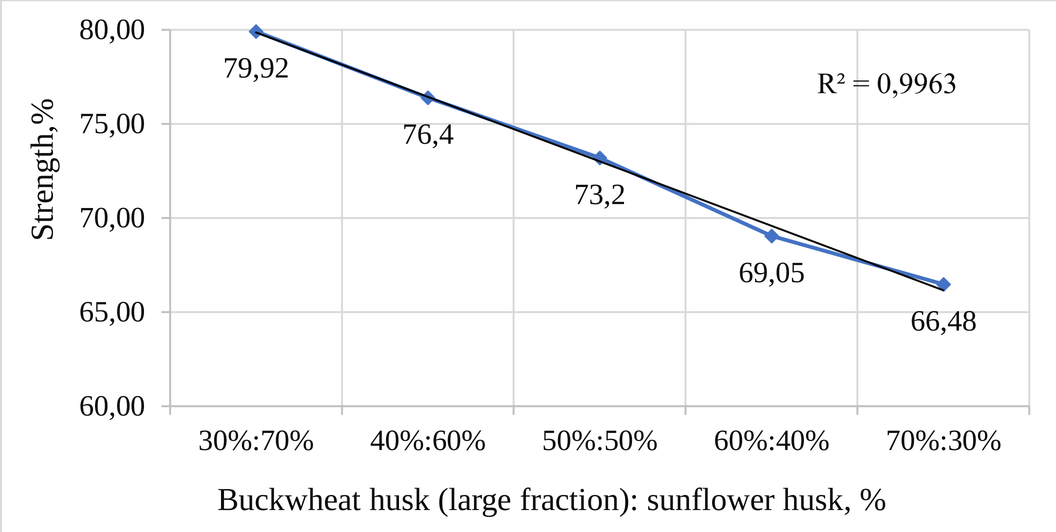


Figure 3.5 – Strength of briquettes made from buckwheat husks (large fraction) and sunflower

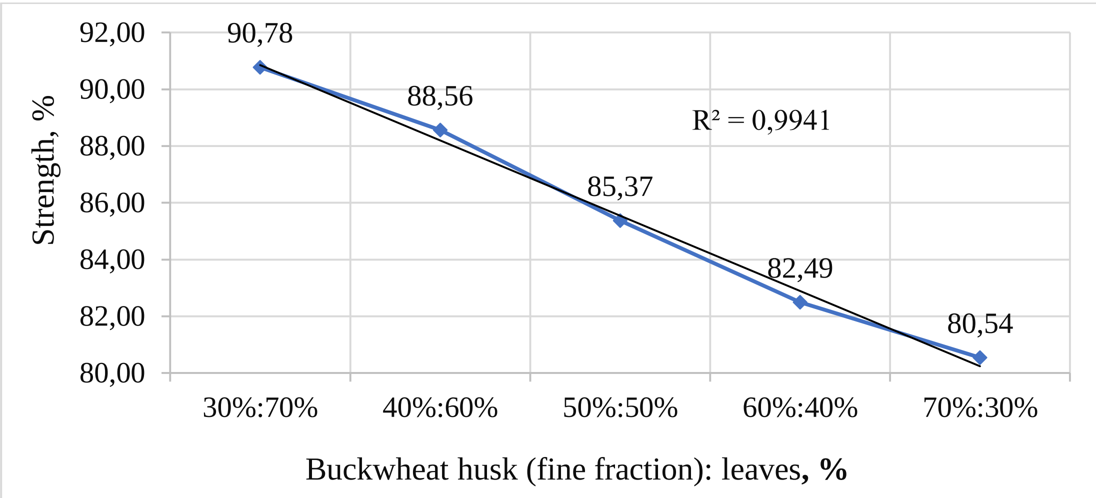


Figure 3.6 – Strength of briquettes made from buckwheat husks (fine fraction) and leaves

In the case of briquettes made from sunflower leaves and husks, the strength of the briquette increases with the increase in leaves in its composition. The dependence is polynomial in nature

$$y = 0.864 \cdot x2 - 2.860 \cdot x + 84.176. \qquad (3.6)$$

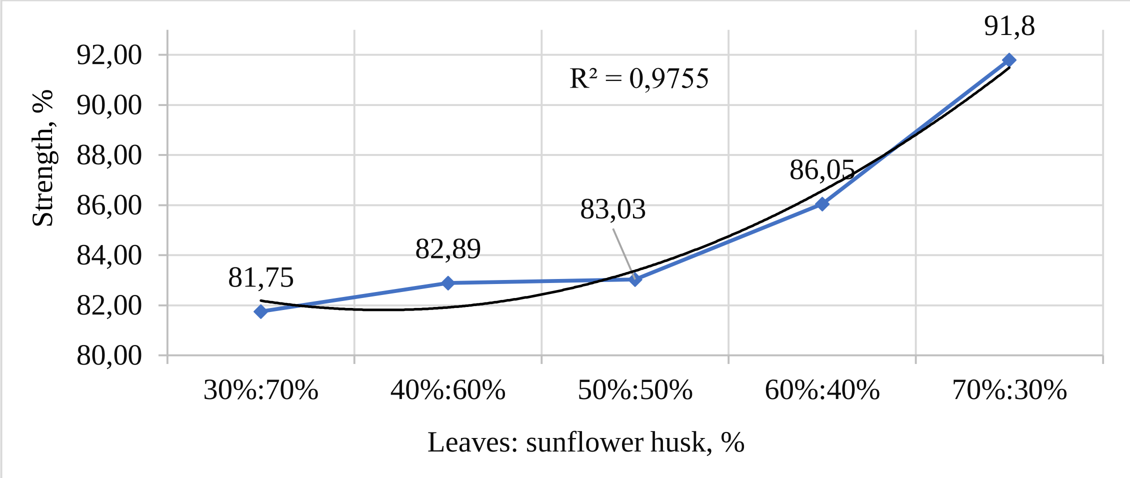


Figure 3.7 – Strength of briquettes made from sunflower leaves and husks

Let us consider on the graph the nature of the change in the strength of briquettes depending on the ratio between the components in its composition (figure 3.8).

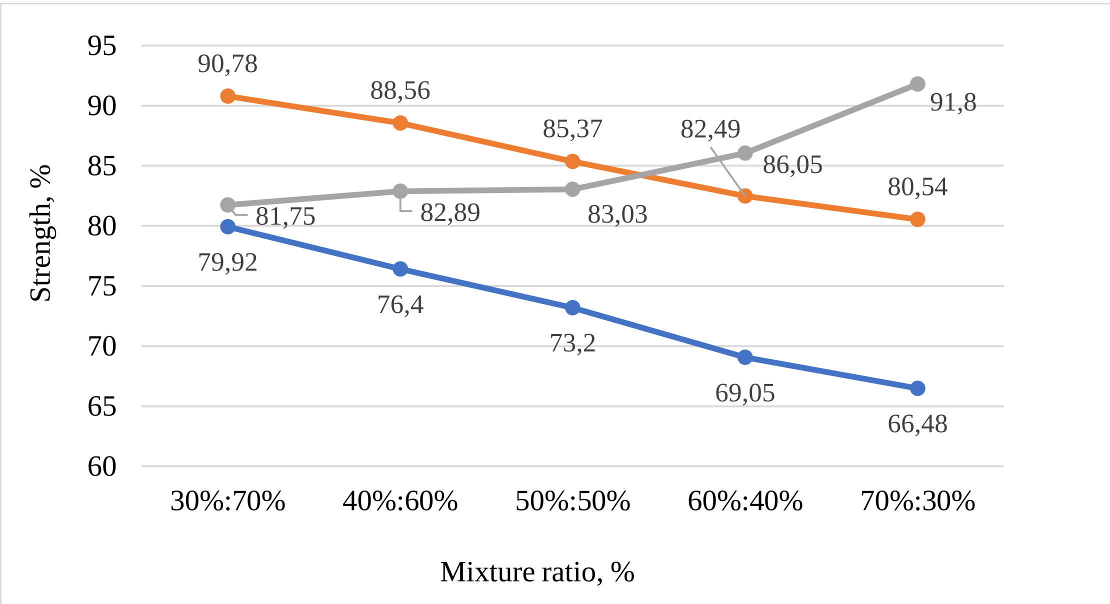


Figure 3.8 – Summary diagram of the dependence of the strength of briquettes on the ratio of components in the mixture

The strength of briquettes containing leaves decreases with a decrease in their proportion in the mixture. These briquettes have a fairly high strength from 80.00 % to 91.80 %, which is a good indicator from the point of view of suitability for transportation. The leaves are easily pressed due to their low density and the presence of lignin. An increase in the content of buckwheat husks, on the contrary, significantly reduces the strength of the briquettes (from 79.92 % to 66.48 %). This is explained by the fact that buckwheat husk has a dense, uneven and dry surface, which is difficult to press.

Such characteristics of briquettes as density and strength are one of the main properties that determine the feasibility of manufacturing and further research of the briquette. Buckwheat husks cannot be pressed without preheating the mixture. The use of buckwheat husks is only possible in conjunction with raw materials that are less dense, uniform and contain a natural binder. The content of leaves in a briquette significantly increases its density, and therefore strength, making it possible to obtain briquettes that are resistant to mechanical stress.

3.1.3 Results of determining the moisture content of briquettes

The moisture content in the briquette reduces the calorific value of the fuel. The acceptable limit for this criterion is 10 %. The results obtained on the moisture content in the briquettes under study are given in table 3.1.

Analysis of the data obtained during the study showed that the moisture content of briquettes lies in the range from 3.50 % to 5.50 %. These values indicate that the briquettes studied meet the recommended moisture content level for biomass fuel. The minimum moisture content (3.39 %) was recorded for a briquette of 70 % leaves and 30% sunflower husks. These briquettes have the lowest moisture content throughout the entire percentage range, ranging from 3.39 % to 3.62 %. This fact is explained by the presence of leaves in the mixture, the moisture content of which is very low (from 2.00 %).

The maximum moisture content in the briquette was 5.50 % (briquette made from 70 % buckwheat husks (large fraction) and 30 % sunflower husks).

The moisture content of briquettes from buckwheat husks (large fraction) and sunflower, as well as briquettes from buckwheat husks and leaves, differ slightly due to the similar moisture content of the feedstock.

Let's look at the graphs (figures 3.9 – 3.12) to see the change in moisture content in briquettes made from buckwheat and sunflower husks, buckwheat husks and leaves, leaves and sunflower husks, depending on the percentage of components.

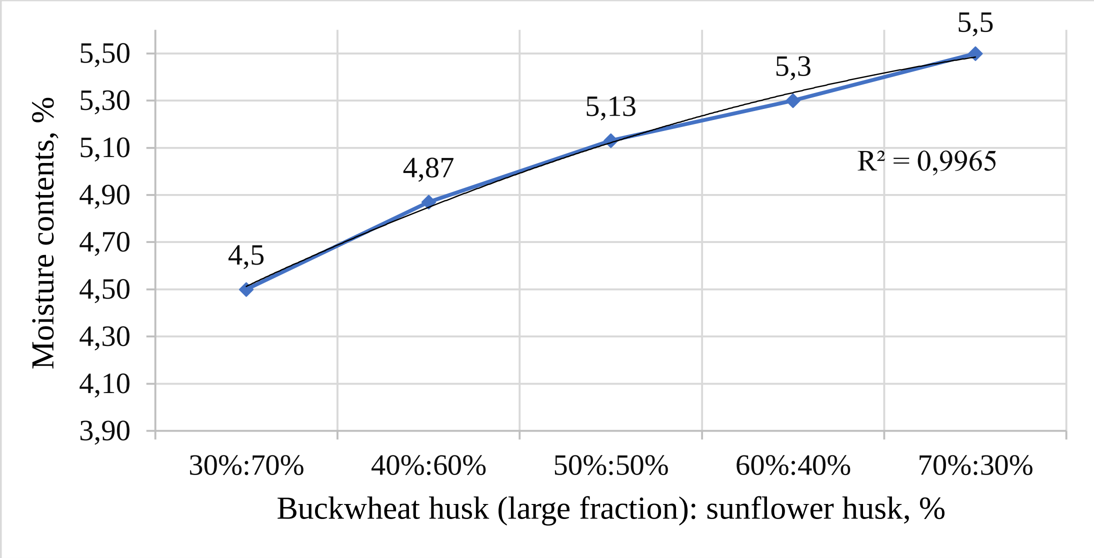


Figure 3.9 – Moisture content in briquettes made from buckwheat husks (large fraction) and sunflower

Analysis of the relationship shown in figure 3.9 indicates an increase in the moisture content in a briquette made from buckwheat husks (large fraction) and sunflower husks with an increase in sunflower husks in its composition. The dependence is polynomial in nature

$$y = -0.031 \cdot x^2 + 0.427 \cdot x + 4.116. \quad (3.7)$$

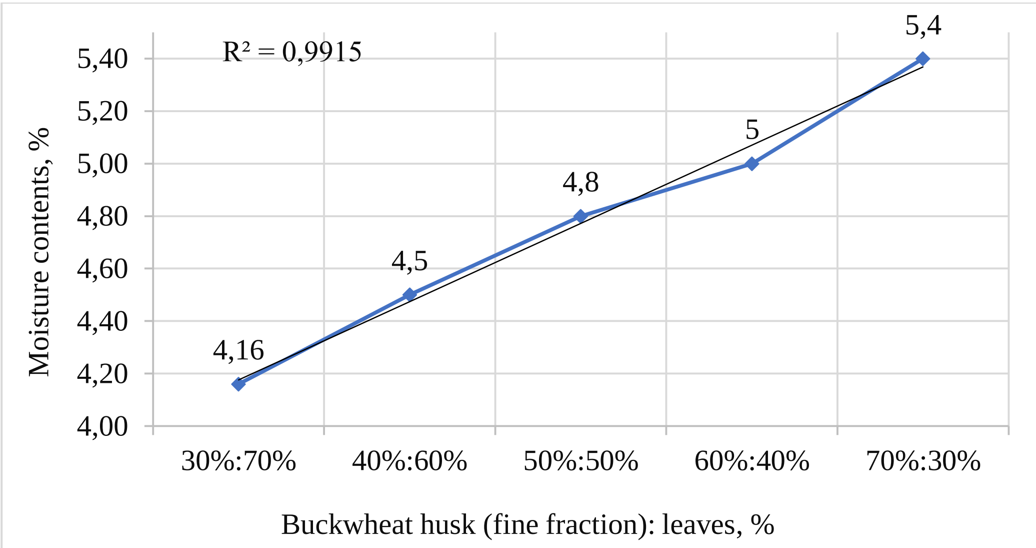


Figure 3.10 – Moisture content in briquettes made from buckwheat husks (fine fraction) and leaves

Figure 3.10 shows the dependence of the moisture content of a briquette made from buckwheat husks (fine fraction) and leaves on its composition. This dependence indicates the following: with an increase in the proportion of buckwheat husks, the moisture content increases. The resulting dependence is linear

$$y = 0.298x + 3.878. \quad (3.8)$$

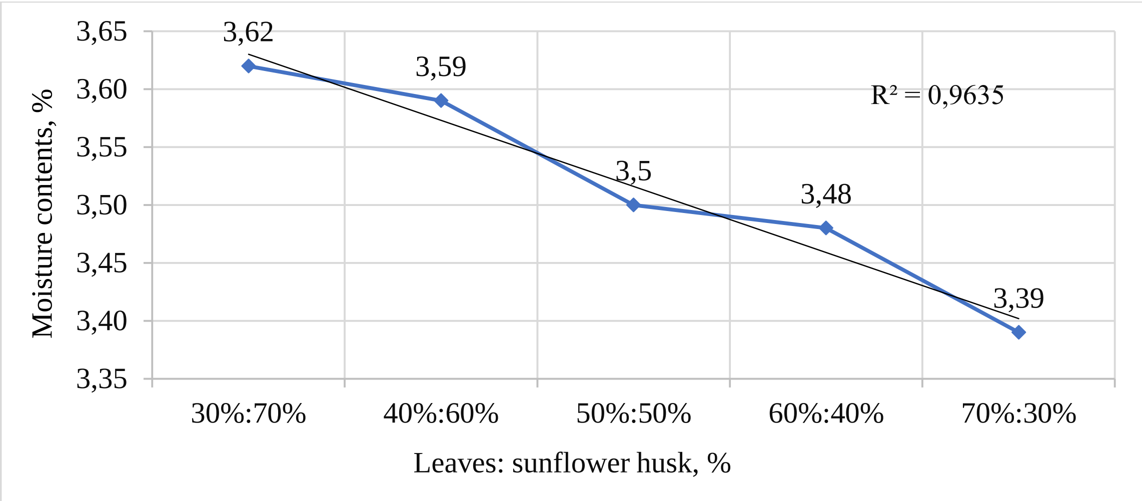


Figure 3.11 – Moisture content in briquettes made from sunflower leaves and husks

In this case, it can be argued that briquettes made from sunflower leaves and husks are characterized by a decrease in moisture with a decrease in sunflower husks in their composition. The dependence under consideration is linear

$$y = -0.057 \cdot x + 3.687. \quad (3.9)$$

The nature of the change in the moisture content of briquettes depending on the ratio between the components in its composition for the briquettes studied is presented in figure 3.12.

Analysis of the obtained dependencies showed that increasing the proportion of buckwheat hulls in the briquette composition increases its humidity to 5.50 %. Briquettes made from sunflower leaves and husks have a lower humidity (3.39 %) compared to other types of briquettes. This is explained by the low leaf moisture content (up to 3.00 %) compared to buckwheat hulls (6.40 %) and sunflower hulls (3.86 %). Therefore, as the proportion of leaves in the mixture increases, the moisture content of the briquettes decreases.

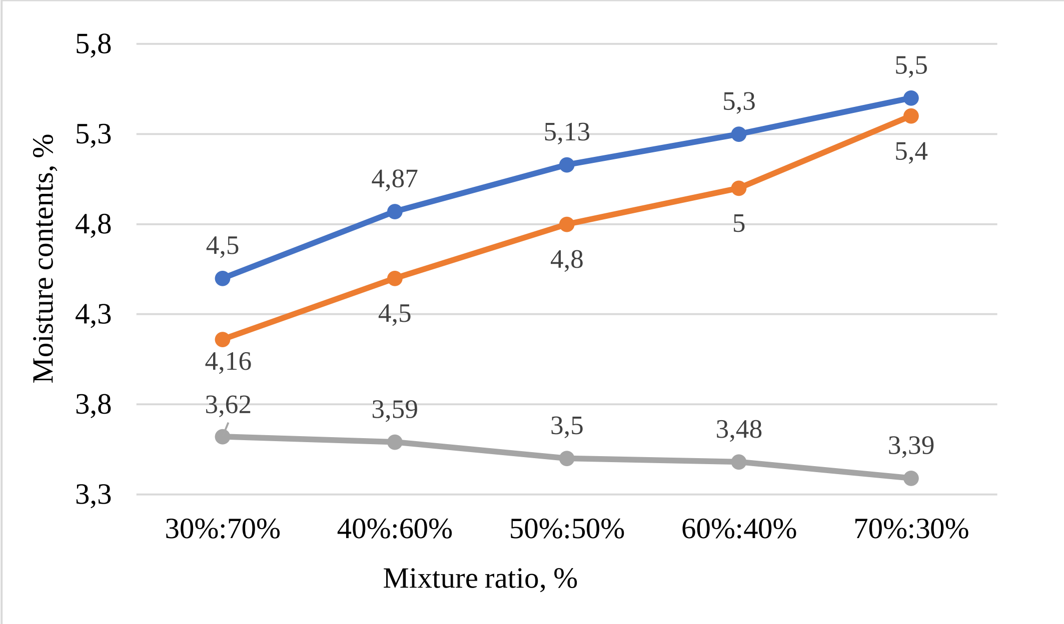


Figure 3.12 – Summary diagram of the dependence of the moisture content of briquettes on the ratio of components in the mixture

3.1.4 Results of the analysis of ash content of briquettes

Ash is an external ballast in the fuel briquette. Increased ash content reduces the calorific value of any fuel, worsens its combustion process, and increases the load on the ash treatment and ash removal system. The results of the study of the ash content of briquettes from agricultural waste were presented in the table 3.1.

Analysis of the results of studying the ash content of briquettes from agricultural waste (table 3.1) showed the following. The maximum ash content (5.40 %) was recorded for a briquette made from 30% buckwheat husks (fine fraction) and 70 % leaves. Increased ash content (5.23 %) was observed in samples of briquettes made from 70 % leaves and 30 % sunflower husks. All briquettes containing leaves are characterized by a high ash content. This is due to the presence of mechanical impurities in the form of sand and soil in the leaves. When organizing preliminary cleaning of leaves, the ash content should decrease.

The minimum ash content (3.00 %) is determined for briquettes made from buckwheat husks (large fraction) and sunflower husks. This ash content value meets the standards [53]. All briquettes of this composition have an ash content that does not exceed standard values.

Figures 3.13 – 3.16 show the change in ash content of briquettes from buckwheat and sunflower husks, buckwheat husks and leaves, leaves and sunflower husks, depending on the percentage of the mixture components.

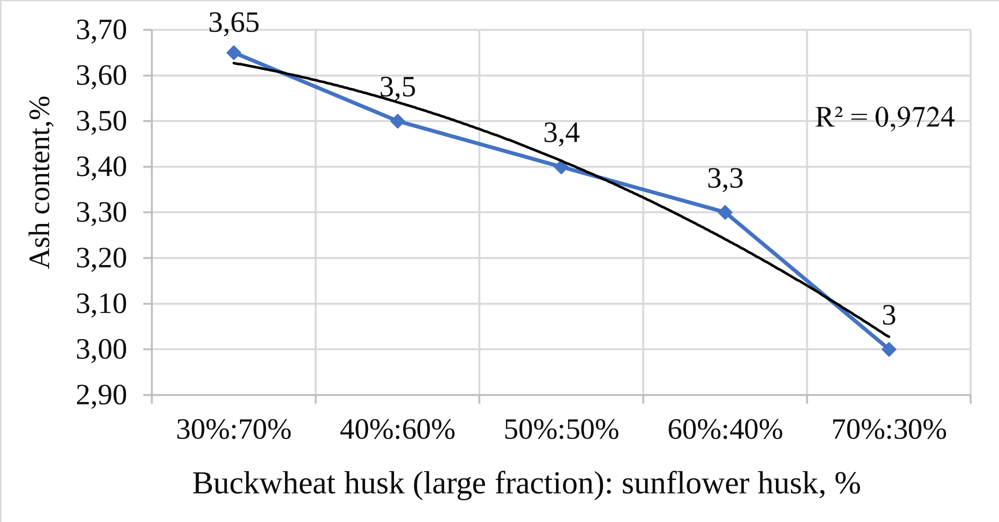


Figure 3.13 – Ash content of briquettes from buckwheat husks (large fraction) and sunflower

Briquettes made from buckwheat husks (large fraction) and sunflower husks are characterized by a decrease in ash content with a decrease in the composition of sunflower husks (figure 3.13). The resulting dependence is polynomial in nature

$$y = -0.021 \cdot x^2 - 0.021 \cdot x + 3.670. \tag{3.10}$$

Analysis of the relationship presented in figure 3.14 indicates a decrease in the ash content of briquettes made from buckwheat husks (fine fraction) and leaves with a decrease in the proportion of leaves in the composition.

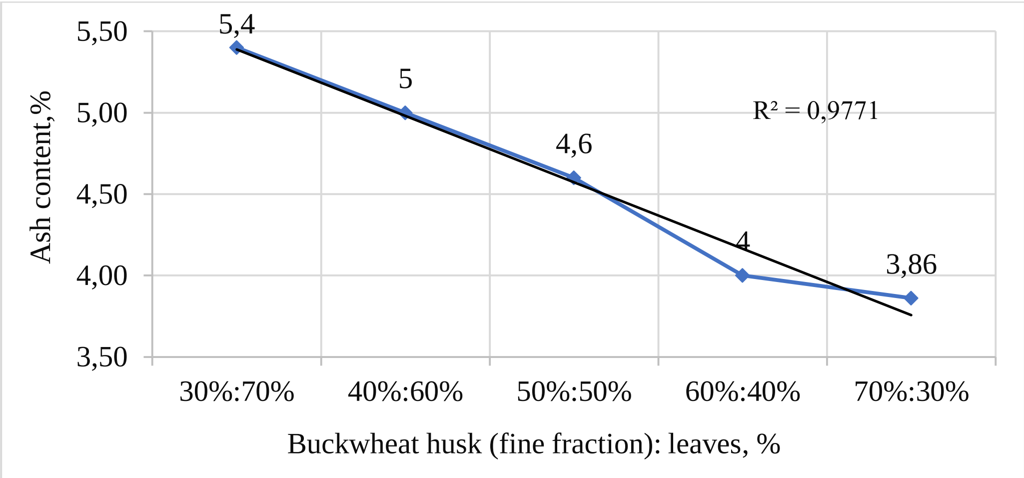


Figure 3.14 – Ash content of briquettes from buckwheat husks (fine fraction) and leaves

The high ash content of these samples is due to the presence of wilted leaves, the ash content of which can reach about 17 %. The surface of the fallen leaves is contaminated with dust, as they were collected in the park area. The approximation of the obtained dependence showed that it is linear

$$y = -0.408 \cdot x + 5.796. \quad (3.11)$$

The ash content of briquettes made from sunflower leaves and husks is presented in figure 3.15.

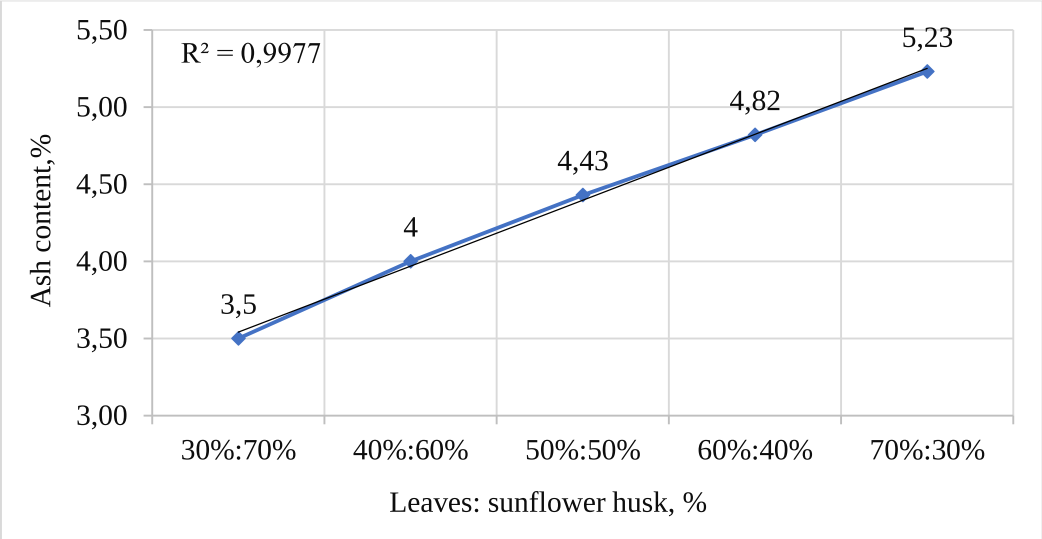


Figure 3.15 – Ash content of briquettes from sunflower leaves and husks

Analysis of the obtained dependence indicates an increase in the ash content of a briquette made from sunflower leaves and husks with an increase in leaves in its composition. Approximation of this dependence showed that it is linear

$$y = 0.428 \cdot x + 3.112. \quad (3.12)$$

Let us analyze the nature of changes in the ash content of briquettes from plant waste depending on the ratio between the components of the mixture (figure 3.16).

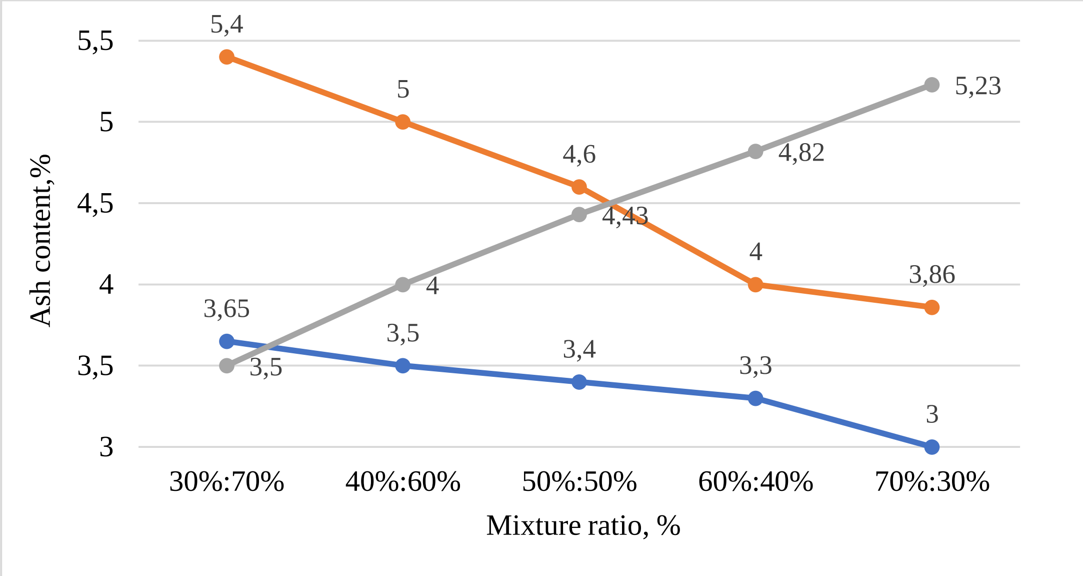


Figure 3.16 – Diagram of the dependence of the ash content of briquettes on the ratio of components

Analyzing the dependencies presented in figure 3.16, we can see that briquettes made from buckwheat and sunflower husks have the lowest ash content (from 3.00 to 3.65 %). This is explained by the low ash content of the feedstock (up to 2.30 %). Briquettes containing leaves as one of the components have a high ash content (up to 5.40 %). This is due to the dustiness of the leaves used. Increasing the proportion of leaves in the mixture increases the ash content of such fuel briquettes.

3.1.5 Results of the study on the release of volatile substances

The release of volatile substances is an important criterion for the fuel combustion process. It indicates the amount of volatile substances that can be released when fuel is burned. Volatiles include gases and vapors that are produced when fuel is heated. They influence the combustion process, are a source of heat and can influence the combustion rate. A high yield of volatiles gives a high reactivity of briquettes, a low yield is the opposite. On the other hand, too high a value has negative aspects: the possibility of fire during storage and a rapid combustion rate, leading to high fuel consumption. The results of the study to determine the yield of volatile briquettes are presented in table 3.1.

Having analyzed the data in Table 3.1, we can conclude that briquettes made from 30 % buckwheat husk (fine fraction) and 70 % leaves have the minimum volatile yield (59.16 %). For briquettes of this type, throughout the entire range of raw material percentages, the volatile yield is lower than for other types of briquettes (from 59.16 % to 67.15 %). This is explained by the presence of leaves in the briquette, the volatile yield of which is low (64 %).

During the experiment, it was found that an increase in the yield of volatiles occurs with a decrease in the content of leaves in the briquette composition. And the increase in the yield of volatiles is associated with the inclusion of sunflower husks in the briquette, the yield of volatiles of which reaches 80 %.

Briquettes made from buckwheat husks and sunflower husks have the highest results in terms of the yield of volatile substances. The maximum value of the yield of volatile substances (81.27 %) was found for a briquette with a percentage of 30 % buckwheat hulls and 70 % sunflower husks.

The graphs (figures 3.17–3.20) show the change in the yield of volatile substances of briquettes from buckwheat and sunflower husks, buckwheat husks and leaves, leaves and sunflower husks, depending on the percentage of components.

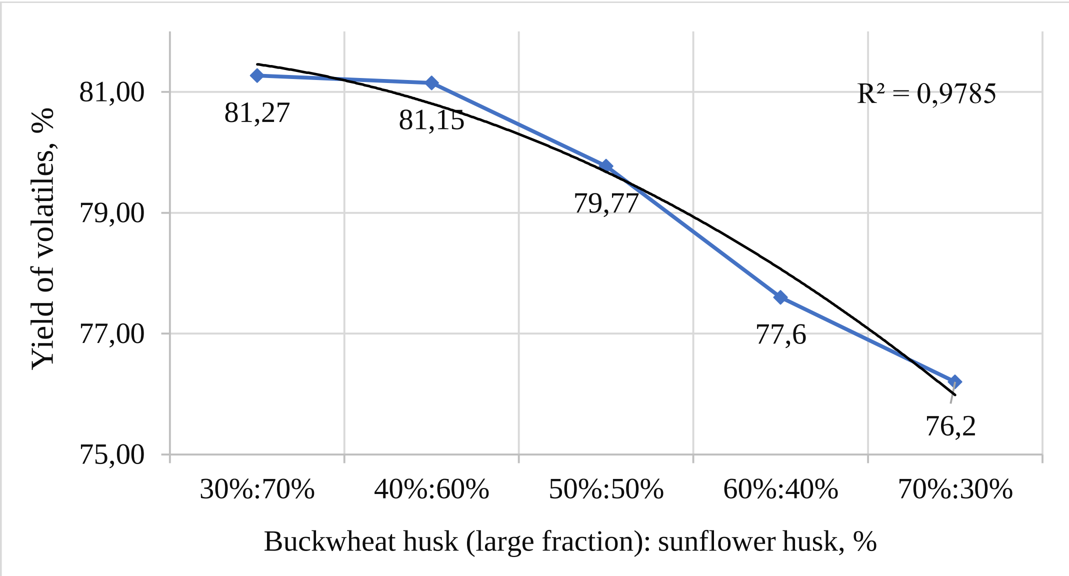


Figure 3.17 – Yield of volatile briquettes from buckwheat husks (large fraction) and sunflower husks

It can be noted that for briquettes made from buckwheat husks (large fraction) and sunflower husks, with a decrease in sunflower husks in its composition, the yield of volatile substances decreases (figure 3.17). Approximation of the obtained dependence gives the polynomial character of the curve

$$y = -0.239 \cdot x^2 + 0.067 \cdot x + 81.630. \qquad (3.13)$$

Figure 3.18 shows the dependence of the yield of volatile substances of briquettes from buckwheat husks (large fraction) and leaves on the percentage composition of the mixture.

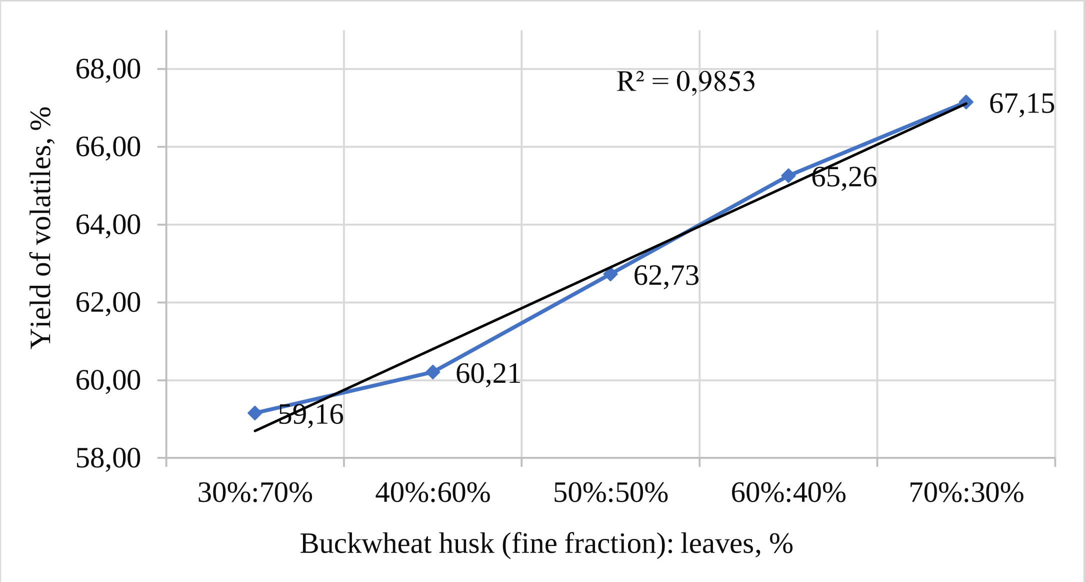


Figure 3.18 – Yield of volatile briquettes from buckwheat husks (fine fraction) and leaves

It has been revealed that with an increase in buckwheat husk in the briquette composition, the yield of volatile substances increases. The resulting dependence is linear

$$y = 2.103 \cdot x + 56.593. \quad (3.14)$$

Analysis of the dependence shown in figure 3.19 indicates that a decrease in the yield of volatile substances for a briquette with sunflower leaves and husks occurs with a decrease in sunflower husks in its composition. The dependence is polynomial in nature

$$y = -0.539 \cdot x^2 + 0.104 \cdot x + 74.298. \quad (3.15)$$

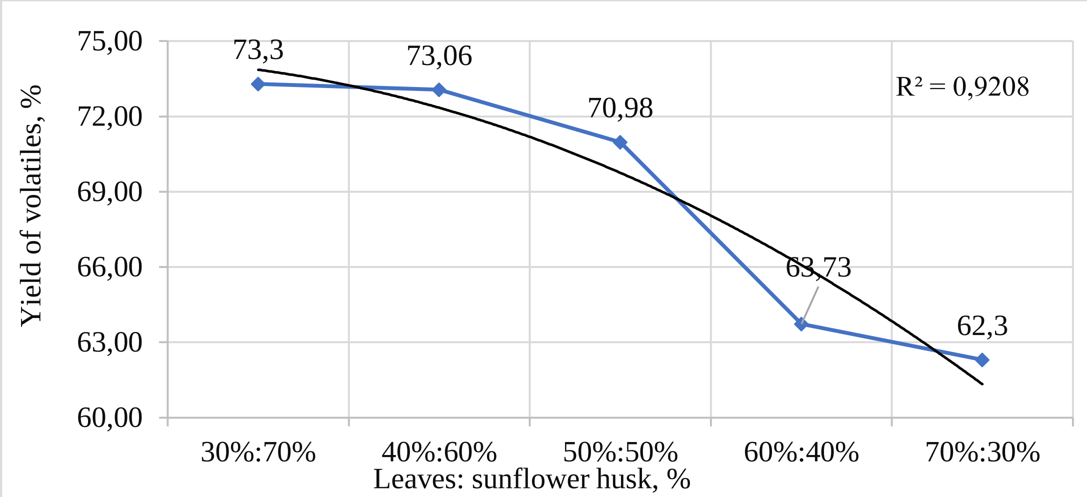


Figure 3.19 – Yield of volatile briquettes from sunflower husk and leaves

Let us consider on the general graph the nature of the change in the yield of volatile substances of briquettes depending on the ratio between the components in its composition (figure 3.20).

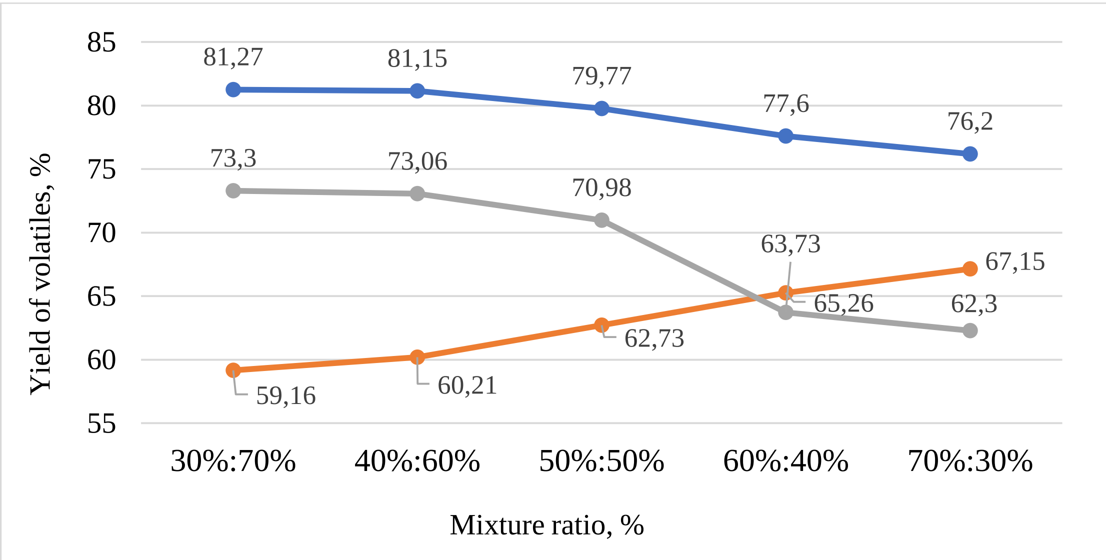


Figure 3.20 – Dependence of the yield of volatile briquettes from plant waste on the ratio of mixture components

A comparative analysis of the obtained dependencies (figure 3.20) showed that the highest yield of volatile substances (up to 81.27 %) was found in samples of briquettes made from buckwheat and sunflower husks. Briquettes containing leaves in their composition have a much lower yield of volatile substances (59.16 %). This is explained by the significant difference in the volatile yield of the feedstock. For example, the yield of volatiles in leaves is 69.30 %, in sunflower husks and buckwheat husks it is above 70 %. Increasing the content of leaves in the composition reduces the yield of volatile substances in the final briquette. An increase in the proportion of buckwheat husks and sunflower husks leads to an increase in this parameter.

Summarizing the data on the study of the yield of volatile substances, we can say the following. Leaves contained in a briquette reduce the yield of volatiles, since they have this parameter lower. The volatile yield of briquettes made from sunflower and buckwheat husks decreases slightly with a change in the ratio of the mixture components, since according to this parameter they have values of the same level. Based on this, these briquettes have the highest yield of volatile substances in all percentages of components in the mixture.

3.1.6 Results of the study on the calorific value of briquettes

The calorific value of briquettes is the amount of heat released during complete combustion of 1 kg of briquettes. The calorific value of briquettes depends on the composition of the briquette and its ash content and humidity. The higher the carbon and hydrogen content in briquettes, the better its calorific value. The higher the calorific value, the more efficient the fuel is used as an energy source. The results of the study on the determination and analysis of the calorific value of briquettes are presented in table 3.1.

Analysis of the data obtained on the calorific value of briquettes from plant waste showed that the lowest calorific value of these briquettes ranges from 17 509.3 kJ/kg to 20 553.5 kJ/kg.

The maximum value of the lower calorific value (20 553.5 kJ/kg) was found for a briquette of 70 % leaves and 30 % sunflower husks. It is worth noting that the content of leaves increases the heat of combustion of the briquette. The heat of combustion of leaves relative to other considered plant agricultural wastes is higher and amounts to 21 206 kJ/kg. The minimum value of the lower calorific value (17 509.3 kJ/kg) was determined for a briquette made of 70% buckwheat hulls and 30 % sunflower hulls. This is due to the lower heat of combustion of buckwheat (17 000 kJ/kg).

On the graphs below (figures 3.21 – 3.24) we will analyze the change in the heat of combustion of briquettes depending on the composition of the mixture.

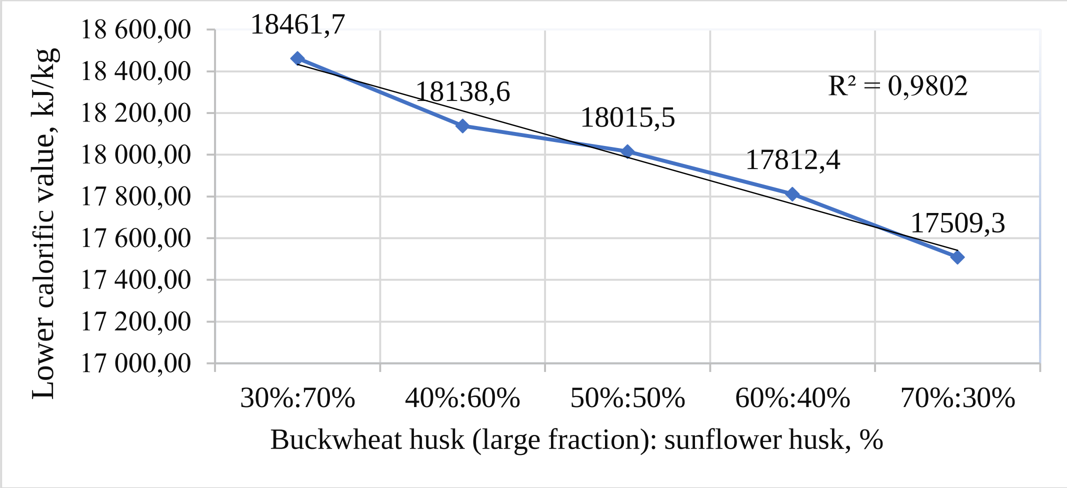


Figure 3.21 – Lower calorific value of briquettes made from buckwheat husks (large fraction) and sunflower husk

It is obvious that for briquettes made from buckwheat and sunflower husks, a decrease in the lower calorific value occurs with a decrease in sunflower husk in its composition. The lower heat of combustion of sunflower husks is greater than that of buckwheat.

Approximation of this dependence showed that it is linear

$$y = -223.1\,x + 18657.0. \qquad (3.16)$$

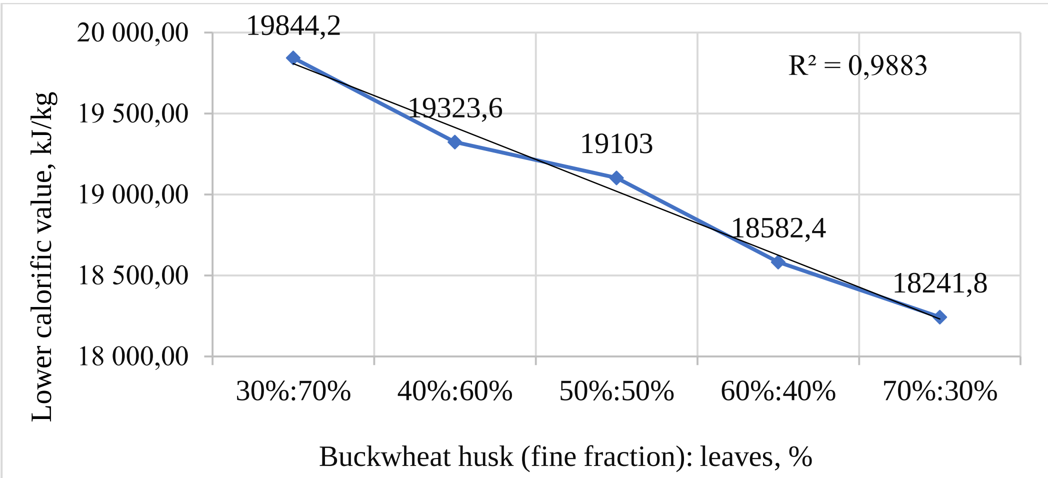


Figure 3.22 – Lower calorific value of briquettes made from buckwheat husks and leaves

In this case (figure 3.22), a decrease in the lower calorific value of briquettes made from buckwheat husks and leaves occurs with a decrease in leaves in its composition. The resulting dependence showed a linear character

$$y = -422.5 \cdot x + 20291.0. \tag{3.17}$$

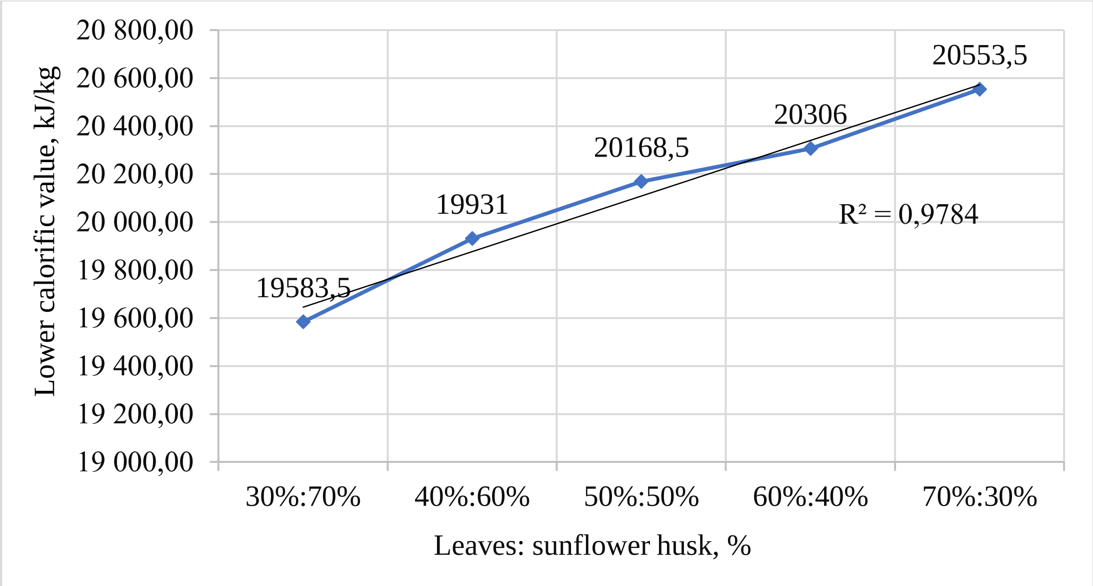


Figure 3.23 – Lower calorific value of briquettes made from sunflower leaves and husks

The obtained dependence (figure 3.23) shows that the lower heat of combustion of briquettes made from sunflower leaves and husks increases with an increase in leaves in its composition. It is worth noting the linear nature of the presented dependence after its approximation

$$y = 231.5 \cdot x + 19414.0. \tag{3.18}$$

Let us conduct a comparative analysis of the nature of the change in the calorific value of briquettes. Let us consider these changes for all types of briquettes depending on the ratio between the components in its composition (figure 3.24).

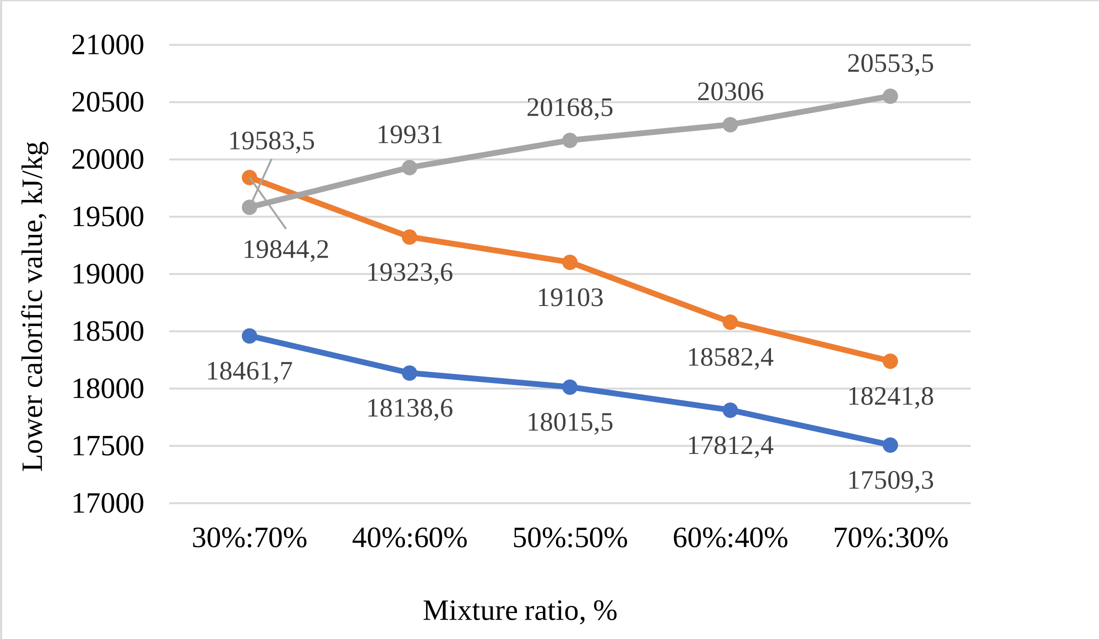


Figure 3.24 – Dependence of the calorific value of briquettes from plant waste on the ratio of components in the mixture

All samples of briquettes made from plant waste have a good calorific value. The highest values of lower calorific value (up to 20.50 MJ/kg) were found for briquettes made from sunflower leaves and husks. The content of leaves in the composition of the fuel briquette increases the lower calorific value. Among the considered plant agricultural wastes, buckwheat husks have the lowest calorific value (17.00 MJ/kg). The results of samples of briquettes containing buckwheat husks are lower than for other types of briquettes. However, these values are optimal for using these briquettes as fuel.

3.2 Results of studies of briquettes from a mixture of plant and industrial waste

Coke dust was used as an industrial waste in the presented study. Coke dust is a waste product from the technological process of the enterprise for the production of calcined petroleum coke (UPNK-PV LLP). Buckwheat and sunflower husks and cake were taken as raw materials of agricultural origin. The results of the study of the thermal characteristics of these briquettes are presented in Table 3.2.

Table 3.2 – Results of experimental studies of combined briquettes from agricultural and industrial waste

№	Mixture ratio, %:%	Density, kg/m^3	Strength, %	Humidity, %	Ash content, %	Volatile yield, %	Heat combustion, J/kg
1	Sunflower husks (fine fraction): coke breeze						
	30:70	897,38	56,28	1,99	6,25	26,65	24479,7
	40:60	943,29	57,32	2,61	5,23	31,99	23882,6
	50:50	957,24	63,61	3,31	2,44	44,00	22685,5
	60:40	976,81	74,60	3,75	1,99	53,71	21988,4
	70:30	1009,27	83,45	4,06	1,35	56,68	21391,3
2	Sunflower cake: coke breeze						
	30:70	1052,33	70,56	1,64	6,76	18,04	24931,8
	40:60	1076,84	81,71	1,79	4,91	26,01	24485,4
	50:50	1182,39	96,19	1,96	4,00	32,36	23739,0
	60:40	1294,31	99,56	2,50	3,03	46,15	22892,6
	70:30	1337,14	99,63	3,00	2,86	55,73	22346,2
3	Buckwheat husk (fine fraction): coke breeze						
	30:70	1101,68	45,12	3,00	5,50	29,74	23909,7
	40:60	1123,82	53,67	3,58	5,20	37,76	23322,6
	50:50	1148,47	66,42	4,00	4,80	40,31	22235,5
	60:40	1156,79	72,06	4,52	4,20	47,62	20948,4
	70:30	1164,55	75,91	5,00	4,00	51,04	19761,3

3.2.1 Results for briquette density

The results of the study of the density of briquettes from agricultural and industrial waste are presented in table 3.2. Analysis of the data obtained showed that the maximum density (1337.14 kg/m^3) has a briquette made of 70 % sunflower cake and 30 % coke breeze. Due to the increased oil content in sunflower cake and its plasticity, such briquettes can be easily pressed. Sunflower cake binds well with coke breeze, allowing you to obtain a fairly dense briquette. The minimum density value (897.38 kg/m^3) was recorded for a sample made from 30 % sunflower husks (fine fraction) and 70 % coke breeze. However, this minimum result complies with the requirements of the European standard [53].

During the experimental study, it was revealed that the density of briquettes containing coke dust increases with the addition of raw materials of organic origin. This is explained by the presence of lignin in the organic structure, which ensures strong adhesion of the mixture components to each other.

Figures 3.25 – 3.28 show graphs of changes in the density of briquettes from agricultural waste depending on the content of coke breeze in the mixture.

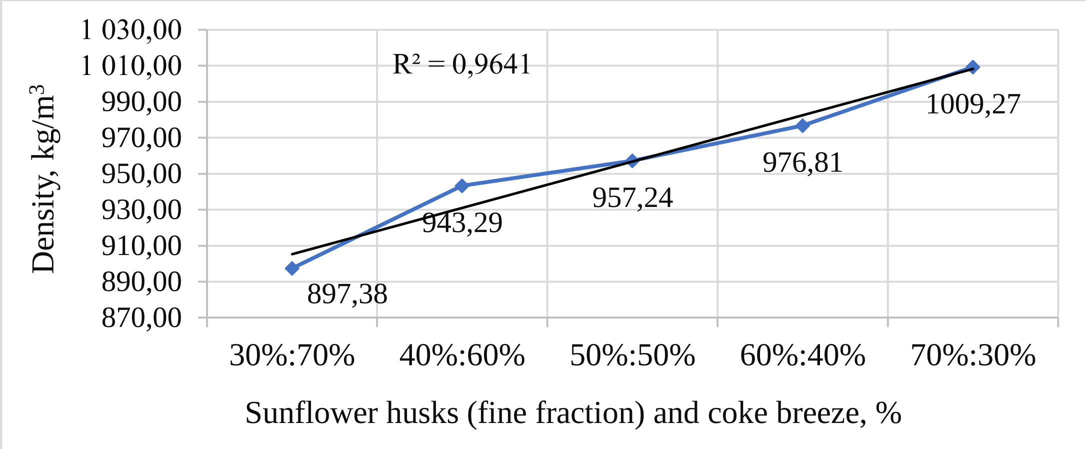


Figure 3.25 – Density of briquettes made from sunflower husks and coke breeze

Figure 3.25 shows the results of an analysis of the density of briquettes made from sunflower husks and coke breeze. The obtained dependence indicates an increase in the density of the briquette made from sunflower husks (fine fraction) and coke breeze with an increase in sunflower husks in its composition.

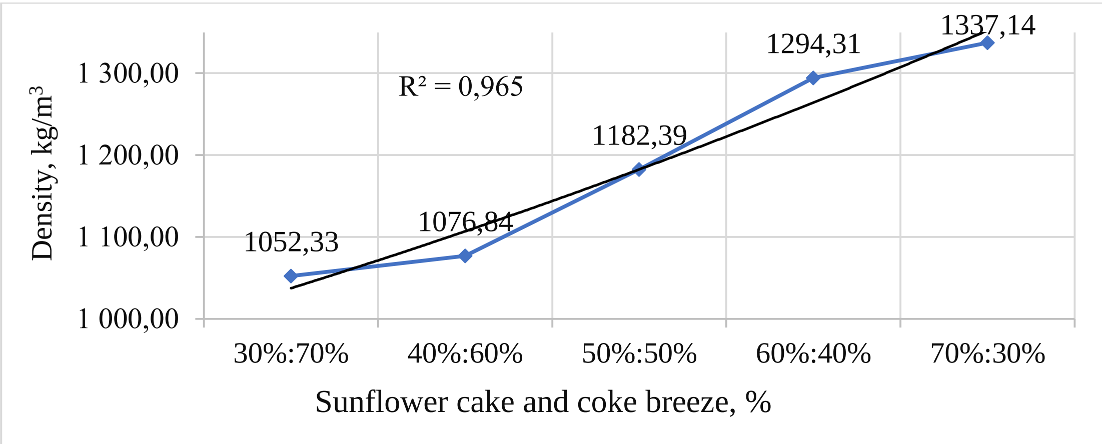


Figure 3.26 – Density of briquettes made from sunflower cake and coke breeze

The resulting dependence based on the approximation results is linear

$$y = 25.730 \cdot x + 879.610. \quad (3.19)$$

Analysis of the dependence (figure 3.26) says that with an increase in the proportion of cake in the briquette composition of sunflower cake and coke breeze, the density increases. The predominant content of sunflower cake in the composition significantly increases the density of the resulting briquette. The oily component of the cake makes it possible to firmly bind the fractions together and facilitates pressing.

Approximation of this dependence showed that it has a polynomial character

$$y = 3.072 \cdot x^2 + 60.276 \cdot x + 973.980. \quad (3.20)$$

Figure 3.27 shows an analysis of the density of briquettes made from buckwheat husks and coke breeze. It can be seen that the density of a briquette made from buckwheat husks and coke breeze increases with the increase in buckwheat husks in its composition.

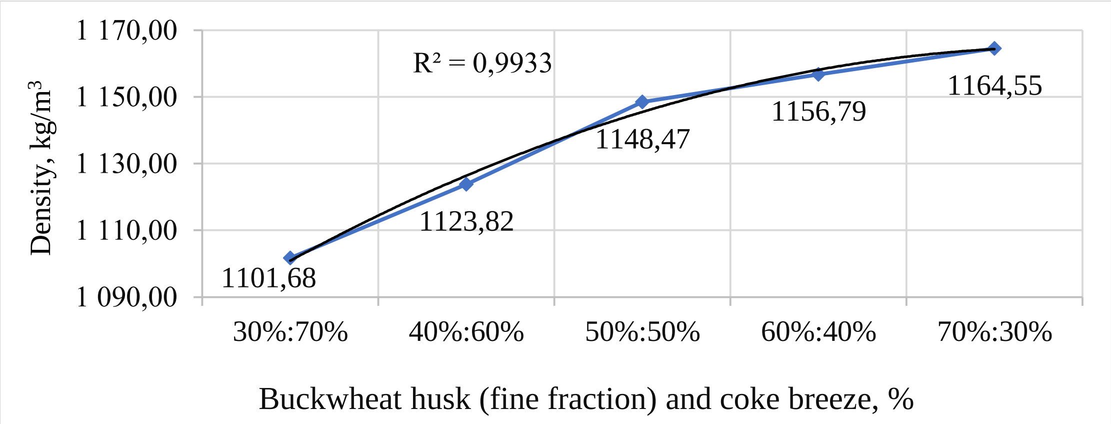


Figure 3.27 – Density of briquettes made from buckwheat husks and coke breeze

The dependence is polynomial in nature

$$y = -3.221 \cdot x^2 + 35.195 \cdot x + 1068.9. \quad (3.21)$$

Let us compare the nature of the change in the density of the briquettes under study when the ratio between the components in the mixture changes (figure 3.28).

It was revealed that briquettes made from buckwheat husks and coke dust have the lowest density (from 897.3 kg/m^3 to 1009.27 kg/m^3). The structure of these briquettes is loose and they are quite easily destroyed by physical impact. Low density and strength are caused by the difficulty of pressing and binding raw material fractions to each other (fine fractions of coke, dryness of both components and uneven surface of buckwheat). Mixing coke breeze, dust with sunflower husks increases the density of briquettes to 1337 kg/m^3 and improves the pressing process.

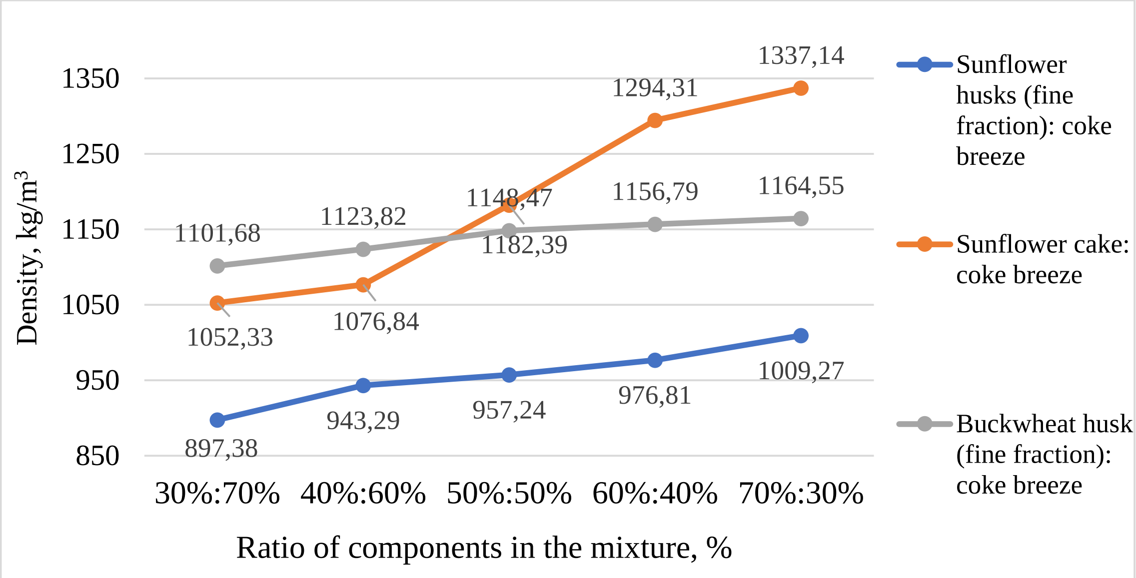


Figure 3.28 – Summary diagram of the dependence of briquette density on the ratio of components in the mixture

It was revealed that for all briquettes, with a decrease in the composition of coke breeze, the density increases. Thus, coke breeze and dust negatively affect the density of the samples.

3.2.2 Results of the study of briquette strength

The results of the study of the strength of briquettes from industrial and agricultural waste are presented in table 3.2.

Briquettes consisting of 70 % sunflower cake and 30 % coke breeze have the maximum strength value (99.63 %). All briquettes of the specified composition are distinguished by high strength characteristics, with the exception of samples in which the proportion of coke dust has a maximum value.

Briquettes made from 30 % buckwheat husk (fine fraction) and 70 % coke breeze have the lowest strength value (45.12 %). Most of this sample consists of coke breeze, which is characterized by fine dispersion and low moisture content. This type of briquettes is extremely fragile and its production is not practical.

Briquettes containing 60 % to 70 % coke breeze are extremely fragile and subject to rapid destruction under the influence of weak forces. The production of briquettes with this ratio of coke in the mixture is impractical.

Let us analyze the change in the strength of briquettes made from sunflower husks (fine fraction), sunflower cake and buckwheat husks depending on the proportion of coke breeze (dust) in the mixture (figures 3.29 – 3.32).

Figure 3.29 shows the dependence of the strength of a briquette made from sunflower husks and coke breeze on the percentage composition of the mixture. The resulting graph characterizes the direct dependence of strength on the proportion of sunflower husks. At the same time, an increase in the strength of the briquette is recorded with an increase in sunflower husk in its composition.

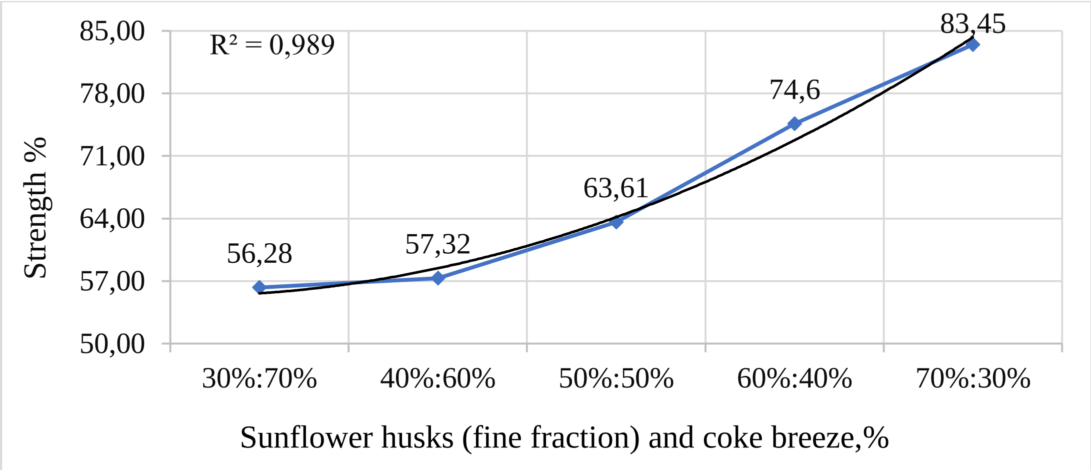


Figure 3.29 – Strength of briquettes made from sunflower husks and coke breeze

The nature of the dependence is polynomial

$$y = 1.451 \cdot x^2 - 1.547 \cdot x + 55.726. \qquad (3.22)$$

Briquettes made from sunflower cake and coke breeze are characterized by an increase in its strength with an increase in the composition of sunflower cake. Sunflower cake improves the bond between the particles of the mixture and leads to an improvement in the strength characteristics of the type of briquette under study (figure 3.30).

The approximation of the presented dependence showed that it has a polynomial character

$$y = -3.805 \cdot x^2 + 32.429 \cdot x + 32.098. \qquad (3.23)$$

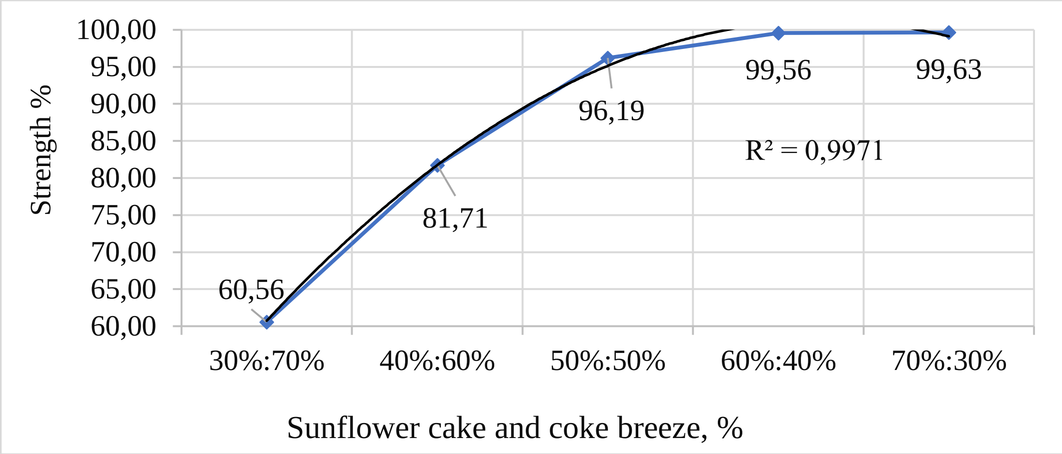


Figure 3.30 – Strength of briquettes made from sunflower cake and coke breeze

In the case of briquettes made from buckwheat husks (fine fraction) and coke breeze, an increase in strength is also demonstrated with an increase in the composition of buckwheat husks and, conversely, a decrease in strength with an increase in the proportion of coke breeze and dust (figure 3.31).

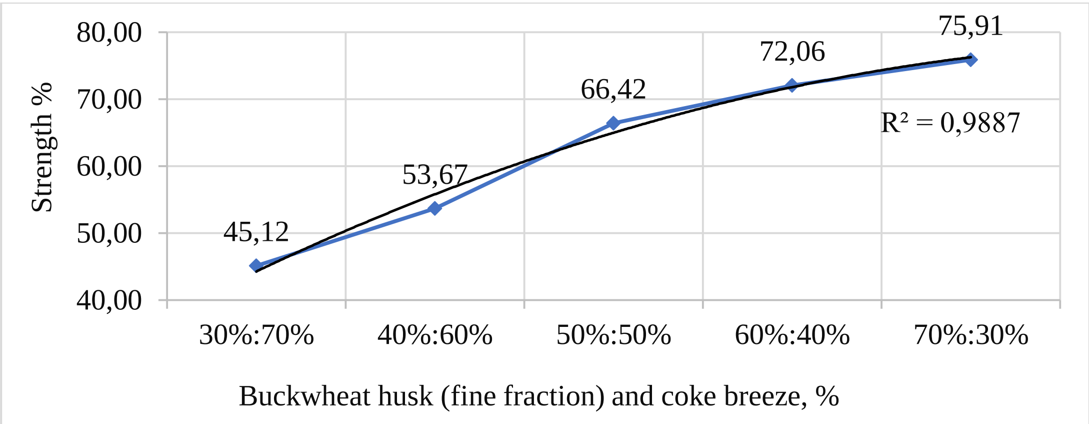


Figure 3.31 – Strength of briquettes made from buckwheat husks and coke breeze

The curve presented in Figure 3.31 has a polynomial character

$$y = -1.179 \cdot x^2 + 15.073 \cdot x + 30.390. \qquad (3.24)$$

Having analyzed the results obtained on the study of the density and strength of briquettes, we can conclude that increasing the proportion of agricultural waste in the mixture increases the density and strength of the briquettes. Agricultural plant waste contains lignin, has higher humidity and larger fraction sizes compared to coke dust. The listed characteristics of plant waste make it possible to improve the binding of mixture components and facilitate the pressing process. Coke dust has a fine and dry structure, which impairs the adhesion between fractions during the pressing process.

Let's compare the nature of the change in the strength of briquettes containing plant waste, depending on the ratio between the components of the briquette (figure 3.32).

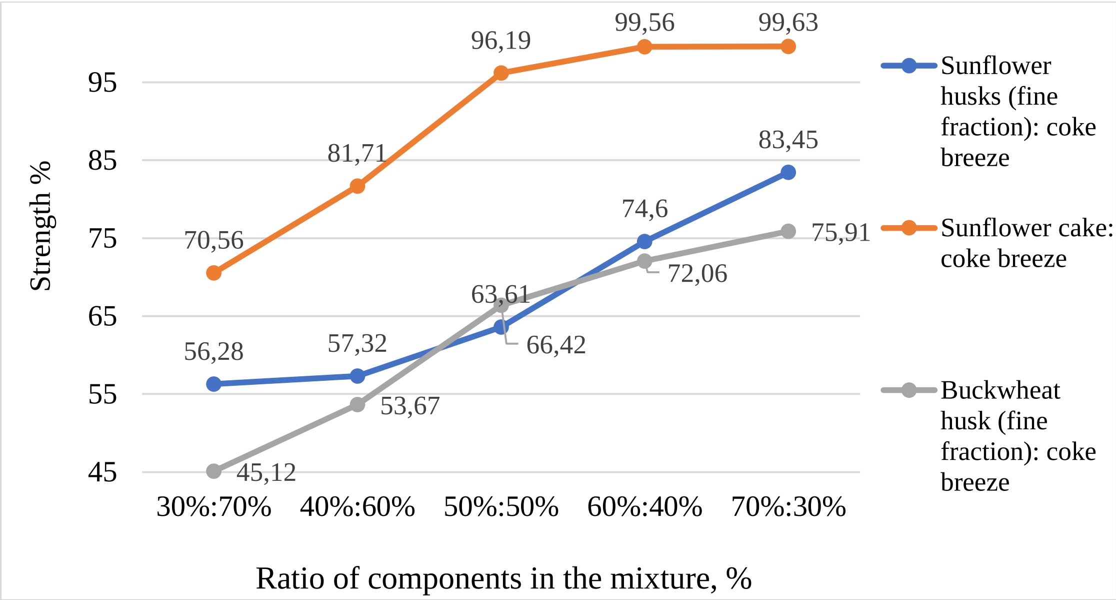


Figure 3.32 – Summary diagram of the dependence of the strength of briquettes on the ratio of components in the mixture

Briquettes made from sunflower cake and coconut fines, if the cake content in the mixture is above 50 %, have high strength (up to 99.63 %). This is due to the oiliness of the cake, which helps improve the process of pressing fine fractions of coke dust. Thus, increasing the proportion of cake in briquettes has a positive effect on its strength and facilitates the pressing process.

Extremely low strength (from 45.12 % to 75.91 %) was detected in briquettes made from buckwheat husks and coke dust in any ratio of mixture components. This fact is explained by the too dry state of both components of the mixture and the fine dispersion of coke dust. Briquettes made from sunflower husks and coke dust are characterized by higher strength (from 56.28 % to 83.45 %). But they are inferior in strength to briquettes made from cake and coke dust.

3.2.3 Results of the study of moisture content of briquettes

Studies have been carried out on the moisture content of briquettes made from industrial and agricultural waste. The obtained results of the moisture content of the briquettes are presented in table 3.2. The content of agricultural plant waste in samples increases the moisture level of the briquette. Coke dust has an extremely low moisture content (1.70 %), an increase in its proportion leads to a decrease in the overall moisture level of the briquette.

The minimum value (1.64 %) was found for a briquette of 30 % sunflower cake and 70 % coke breeze. For samples with this mixture composition in all percentages of raw materials, the moisture level does not exceed 3.00 %. The maximum moisture content (5.00 %) was recorded for a briquette made of 70 % buckwheat husk (large fraction) and 30 % coke breeze. Increased humidity is observed in briquettes that contain buckwheat husks.

However, all briquette samples showed moisture levels that met the standard requirements.

Let us examine in more detail (figures 3.33–3.36) the change in moisture content in briquettes made from sunflower husks (fine fraction), sunflower cake and buckwheat husks depending on the percentage of coke breeze and dust in the mixture.

The moisture content in a briquette made from sunflower husks (large fraction) and coke breeze ranges from 1.99 % to 4.06 %. With an increase in sunflower husk in its composition, the humidity increases. Low humidity in samples with a predominant content of coconut fines (dust) can be explained by the low humidity of the feedstock (from 1.70 % to 3.00 %).

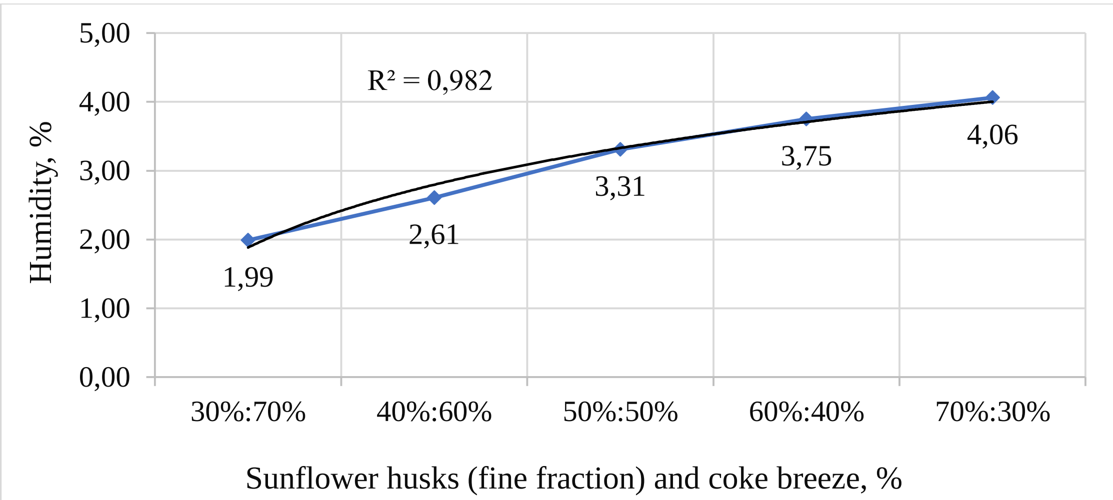


Figure 3.33 – Moisture content in briquettes made from sunflower husks and coke breeze

The approximation curve is logarithmic in nature

$$y = 1.317 \cdot \ln(x) + 1.884. \quad (3.25)$$

The moisture content in briquettes made from sunflower cake and coke breeze (figure 3.34) varies from 1.34 % to 3.00 %. Humidity increases with increasing sunflower cake composition. Cake, like sunflower husks, have a moisture content ranging from 3.00 % to 4.00 %, which is higher than the initial moisture content of coke dust (1.70 %).

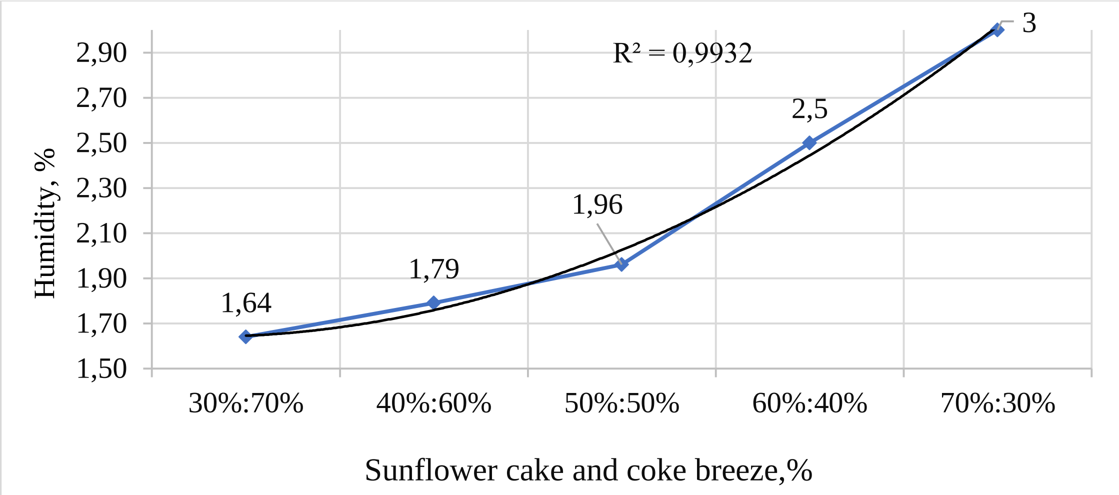


Figure 3.34 – Moisture content in briquettes made from sunflower cake and coke breeze [40]

Approximation of this dependence showed that it has a polynomial character

$$y = 0.076 \cdot x^2 - 0.116 \cdot x + 1.684. \quad (3.26)$$

Figure 3.35 shows the results of the analysis of moisture content in briquettes made from buckwheat husks and coke breeze. They indicate an increase in the moisture content in the briquette with an increase in buckwheat husk in its composition. The moisture level in a briquette of this composition ranges from 3 % to 5 %. These are the highest moisture values among the briquette types studied.

The approximation curve is linear

$$y = 0{,}494 \cdot x + 2{,}538. \quad (3.27)$$

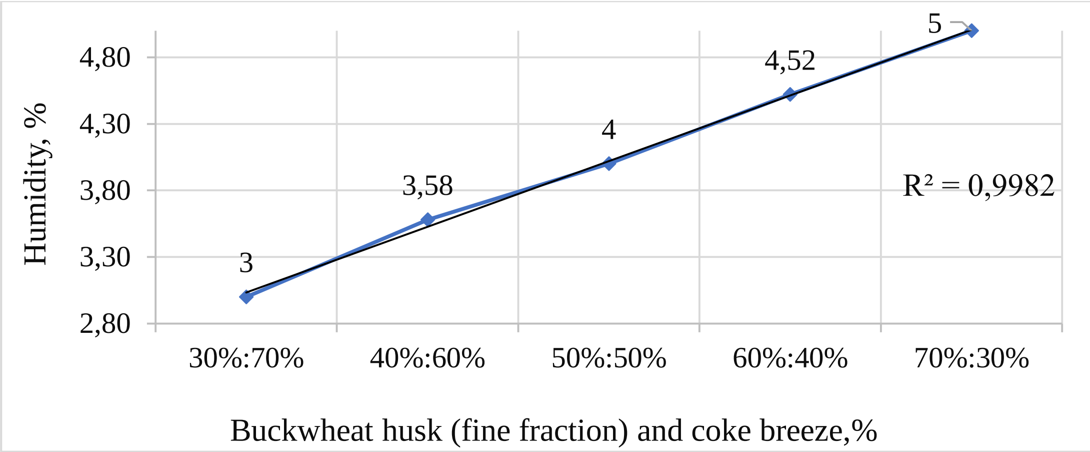


Figure 3.35 – Moisture content in briquettes made from buckwheat husks and coke breeze

A comparative analysis of changes in the moisture content of the resulting briquettes from industrial and agricultural waste is presented in Figure 3.36. It has been established that the moisture content of a briquette varies depending on the ratio between the components in its composition.

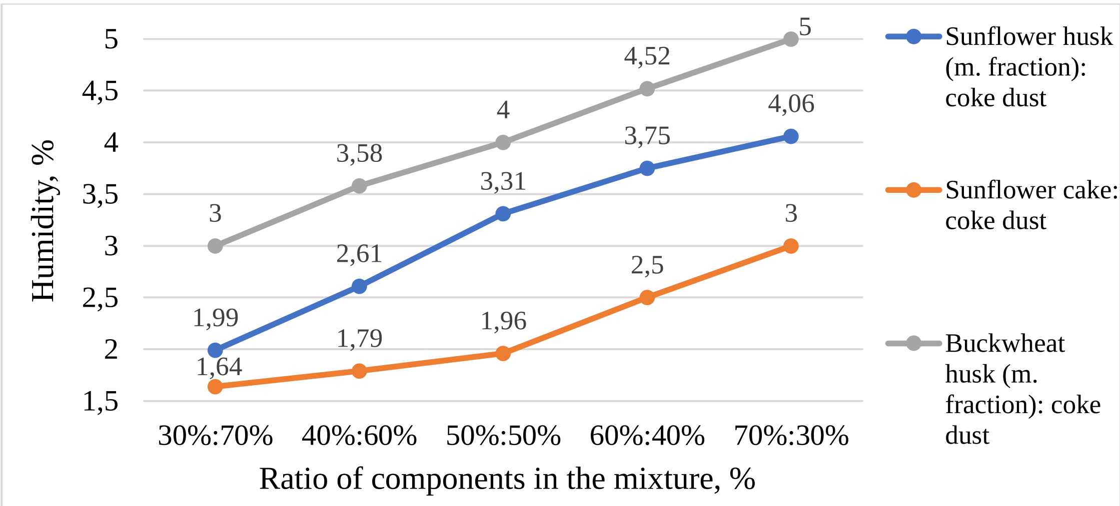


Figure 3.36 – Comparative analysis of the moisture level of briquettes depending on the ratio of components in the mixture

Analyzing these curves, we can conclude that the moisture content of the briquettes is directly dependent on the composition of the mixture. Moreover, an increase in the percentage of plant waste mixed with coke breeze increases the moisture level in all briquettes under study (from

1.64 % to 5.00 %). This is explained by the fact that the moisture content in waste of plant origin (up to 6.00%) is higher than that of coke dust.

3.2.4 Results of the study on ash content of briquettes

An analysis of the ash content of briquettes from industrial and agricultural waste was carried out. The results of the study of the ash content of briquettes are presented in table 3.2. The level of ash in the briquettes under study ranges from 1.07 % to 6.76 %. This value meets the requirements of standards for the quality of fuel briquettes. It has been experimentally established that with an increase in the proportion of coke breeze and dust in the composition, the ash content of the final briquette increases. This is explained by the increased ash content in the coke component (6.65 %).

The maximum level of ash content (6.76 %) was found in briquettes with a coke component over 60%.

The minimum ash content (1.35 %) was recorded for a briquette made from 70 % sunflower husks (fine fraction) and 30 % coke breeze.

Let's consider (figures 3.37–3.40) the change in ash content of briquettes made from sunflower husks (fine fraction), sunflower cake and buckwheat husks depending on the percentage of coke breeze in the briquette.

Let's consider how the ash content of a briquette made from sunflower husks and coke dust changes as the composition of the sample changes (figure 3.37).

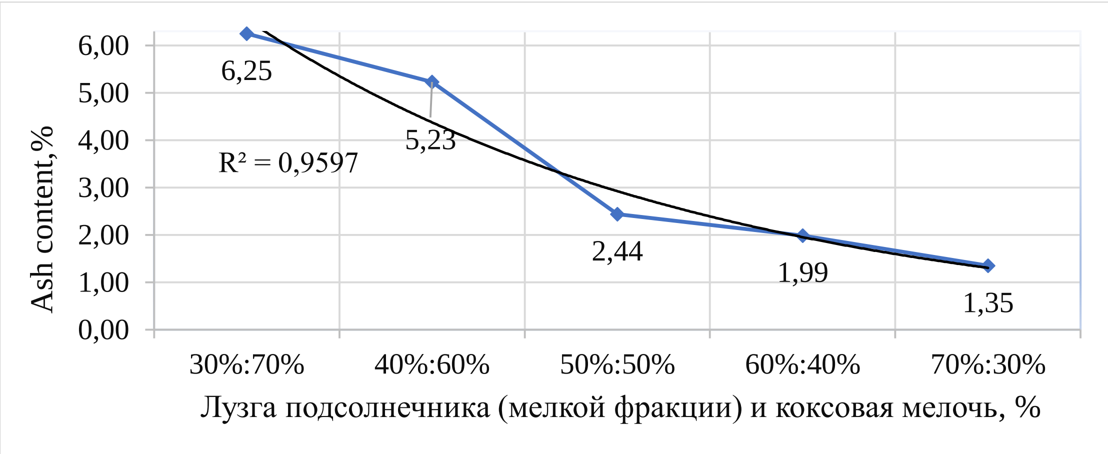


Figure 3.37 – Ash content of briquettes from sunflower husks and coke dust

Analysis of the dependence indicates a decrease in the ash content of the fuel briquette from 6.25 % to 1.35 % with a decrease in coke dust in its composition. In briquettes, coke dust makes up a significant part of the mixture, and there is an increased ash content. This is explained by the ash content of the coke itself (6.65 %), which is significantly higher than the ash content of sunflower husks (2.06 %).

The dependence obtained during the approximation is an exponential

$$y = 9.804 \cdot e^{-0,403x}. \quad (3.28)$$

The ash content of briquettes from sunflower cake and coke breeze (figure 3.38) also shows a decrease in ash content from 6.76 % to 2.86 % with a decrease in coke dust in its composition.

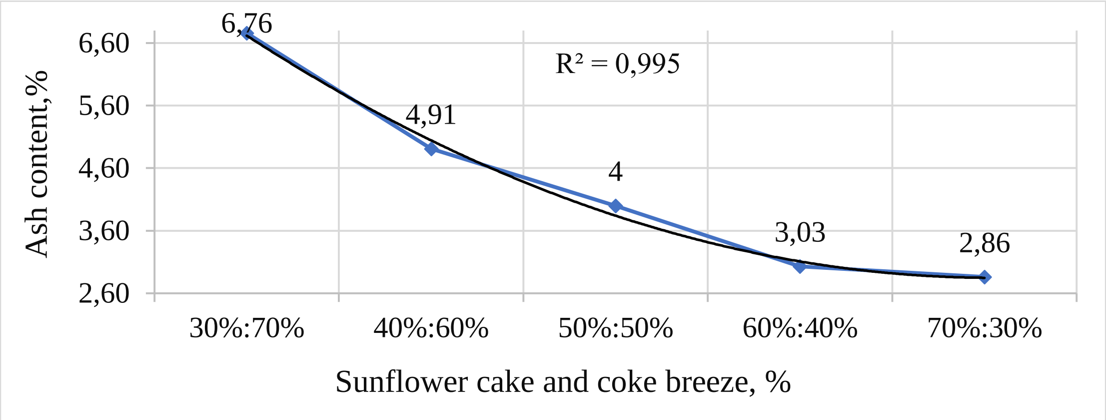


Figure 3.38 – Ash content of briquettes from sunflower cake and coke breeze

Approximation of this dependence showed that it has a polynomial character

$$y = 0.236 \cdot x^2 - 2.382 \cdot x + 8.866. \quad (3.29)$$

Figure 3.39 shows the results of a study of the ash content of briquettes made from buckwheat husks and coke dust. They indicate a decrease in ash content with a decrease in the proportion of coke dust in the composition (from 5.5 % to 4.0 %).

The approximation curve is linear

$$y = -0.385 \cdot x + 5.925. \quad (3.30)$$

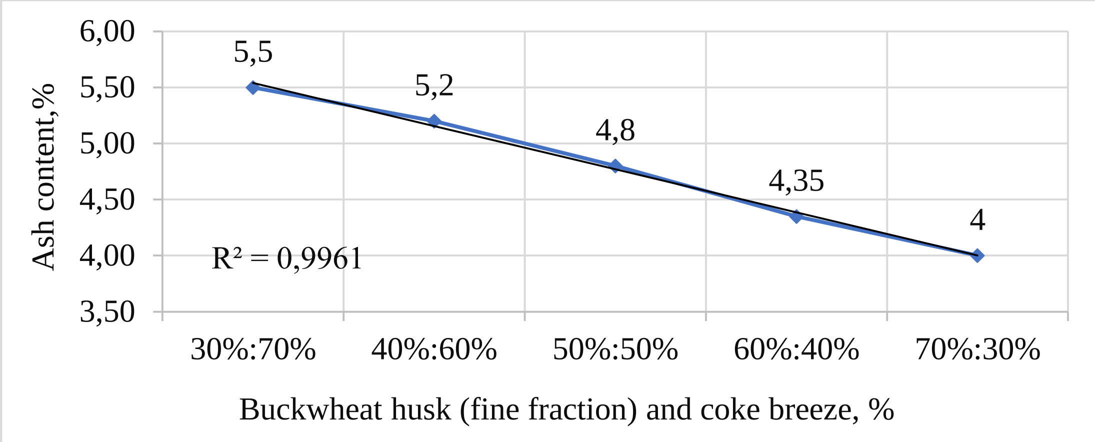


Figure 3.39 – Ash content of briquettes made from buckwheat husks and coke dust

A comparative analysis of the nature of changes in the ash content of briquettes depending on the ratio between the components in its composition is presented in figure 3.40.

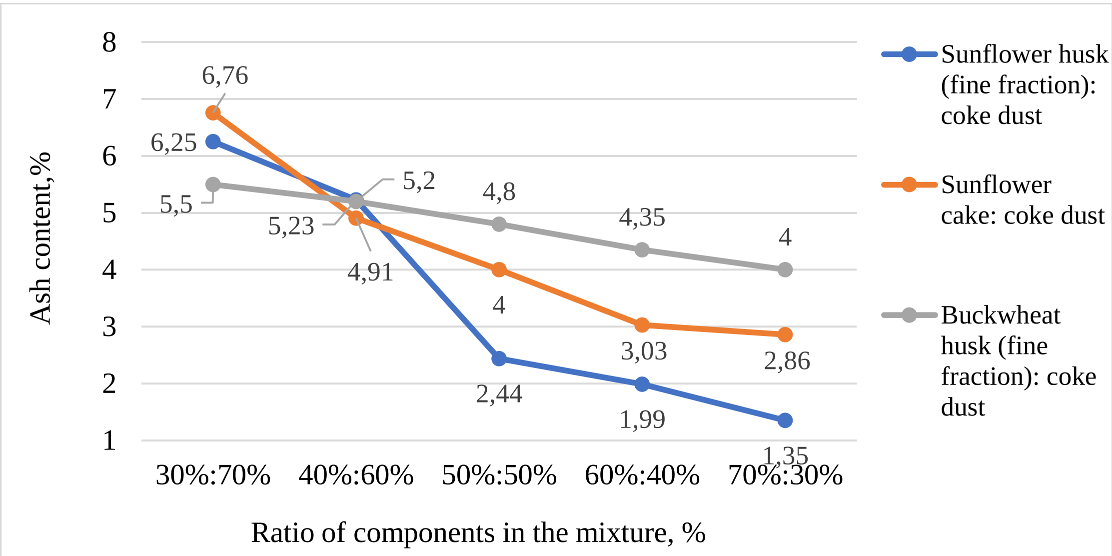


Figure 3.40 – Summary diagram of the dependence of the ash content of briquettes on the ratio of components in the mixture

The ash content of samples of briquettes from industrial and plant waste submitted for analysis ranges from 1.35 % to 6.76 %. Moreover, an increase in the content of plant waste in a mixture with coke breeze reduces the ash content in all briquettes studied. This fact can be explained by the lower level of ash content of the original plant raw materials (from 2.26 % to 4.00 %) compared to the ash content of coconut dust (6.65 %).

3.2.5 Results of volatile emission analysis

An analysis was carried out of the release of volatile substances from bricks from industrial and agricultural plant waste. The results of the study are presented in table 3.2. The minimum yield of volatiles (18.1 %) was detected in briquettes made from sunflower cake and coke dust. This result is very different from the value that was recorded for briquettes made only from plant components (59.16 %). This can be explained by the low yield of volatile substances from coke dust (9.81 %). A low yield of volatile substances characterizes the weak reactivity of briquettes, which can complicate the ignition process.

The maximum yield of volatiles (56.68 %) was determined for a sample of 60 % sunflower husk and 40 % coke dust. Increasing the proportion of plant raw materials in the mixture allows increasing the yield of volatiles to satisfactory values.

Figures 3.41–3.44 show the results of the analysis of the change in the yield of volatile substances of briquettes from sunflower husks (fine fraction), sunflower cake and buckwheat husks depending on the percentage of coke dust.

Figure 3.41 shows the dependence of the yield of volatile substances from a briquette with sunflower husks (fine fraction) and coke breeze. It indicates that an increase in the yield of volatile substances from 26.65 % to 56.68 % occurs with an increase in the composition of sunflower husks. The low yield of volatiles in samples with mixture ratios of 30%:70% and 40 %:60 % can be explained by the low yield of volatile coke breeze (9.81 %). This complicates the ignition process and the rate of ignition of the briquettes.

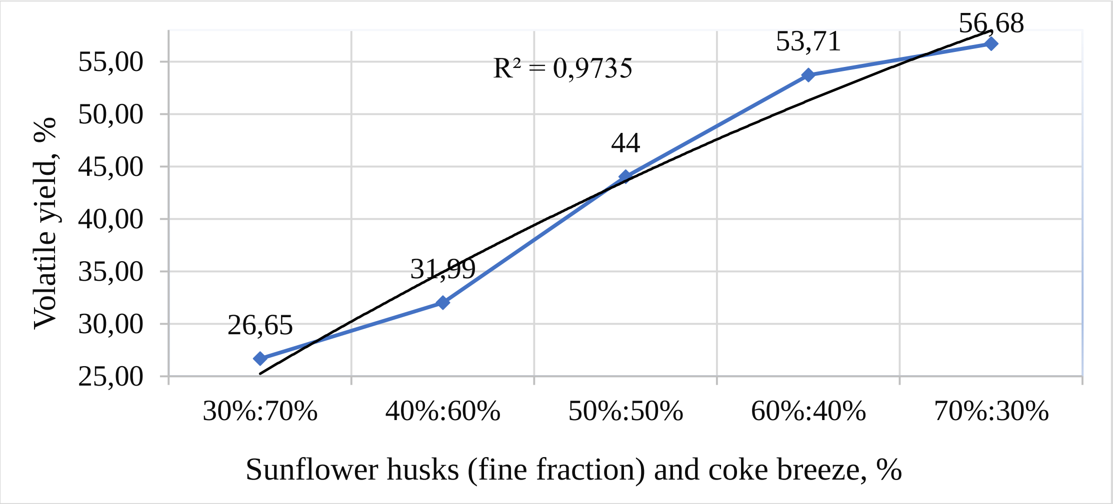


Figure 3.41 – Yield of volatile briquettes from sunflower husks and coke breeze

The approximation showed that the presented function has a polynomial character

$$y = -0.503 \cdot x^2 + 11.195 \cdot x + 14.552. \qquad (3.31)$$

Figure 3.42 shows the results of a study of the yield of volatile briquettes from sunflower cake and coke dust. The yield of volatile substances increases from 18.04 % to 55.73 % with an increase in the proportion of sunflower cake in its composition.

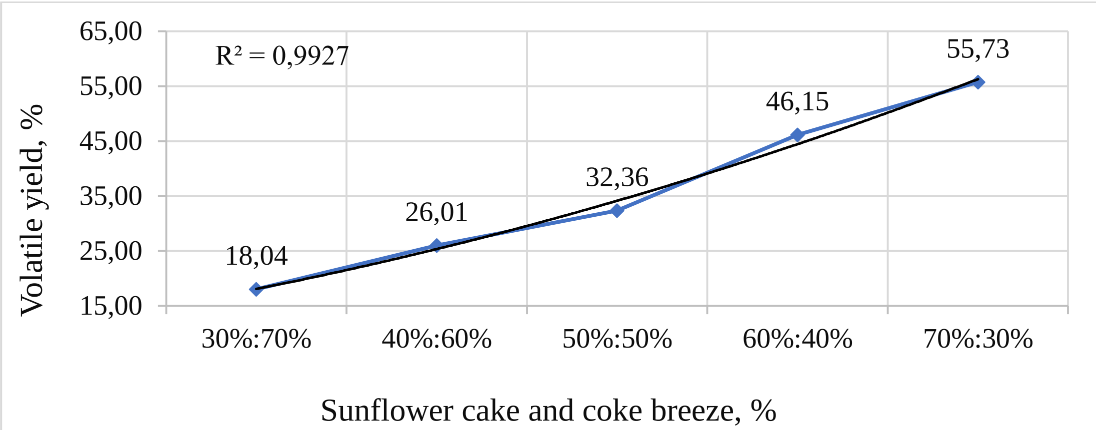


Figure 3.42 – Yield of volatile briquettes from sunflower cake and coke dust

Approximation of this dependence showed that it has a polynomial character

$$y = 0.761 \cdot x^2 + 4.983 \cdot x + 12.332. \qquad (3.32)$$

The results of the analysis of the volatile yield of briquettes from sunflower husks mixed with coke dust are presented in figure 3.43. The volatile yield increases from 29.74 % to 51.04 %. Moreover, the increase in the yield of volatile substances is associated with the growth of buckwheat husk in the mixture.

Approximation of this dependence showed that it is linear

$$y = 5.246 \cdot x + 25.556. \qquad (3.33)$$

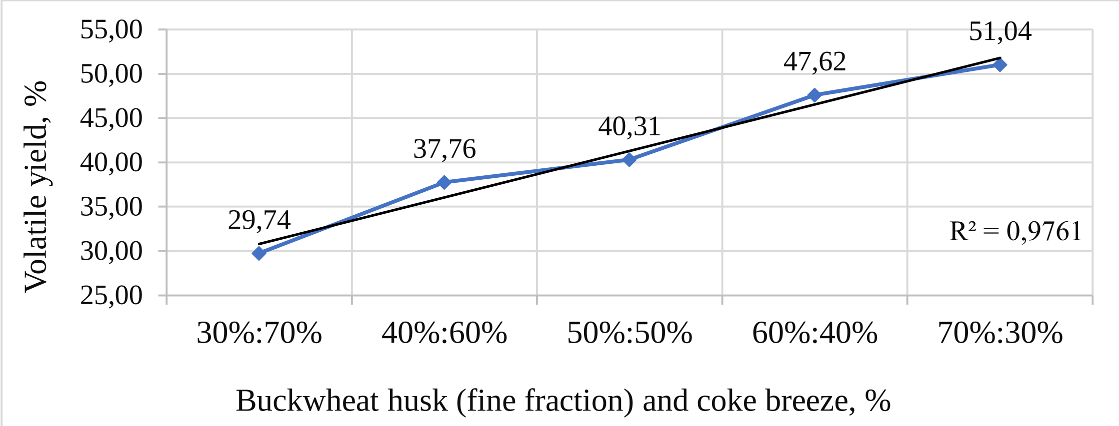


Figure 3.43 – Yield of volatile briquettes from buckwheat husks and coke breeze

Let us conduct a comparative analysis of the nature of the change in the yield of volatile substances of briquettes depending on the ratio between the components in its composition (figure 3.44).

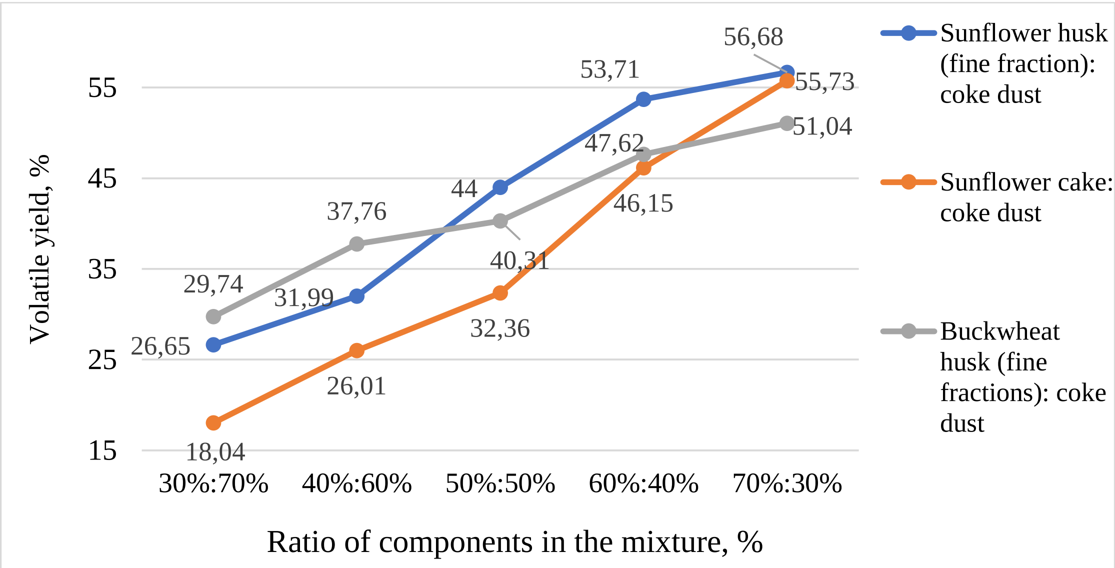


Figure 3.44 – Summary diagram of the dependence of the yield of volatile briquettes on the ratio of components in the mixture

Analysis of the dependencies (figure 3.44) showed that increasing the content of agricultural plant waste in a mixture with coke breeze increases the yield of volatile substances in all types of briquettes. This is explained by the fact that the yield of volatile substances from plant waste (from 55 % to 80 %) significantly exceeds the yield of volatile substances from coconut dust (9.81 %).

3.2.6 Results of studies to determine the calorific value of briquettes

The results of studies to determine the calorific value of combined fuel briquettes are presented in table 3.2. The lower calorific value of the briquettes under study has fairly good values. The heat content of briquettes varies from 19 761.3 kJ/kg to 24 479.7 kJ/kg. For comparison, the lower calorific value of Ekibastuz coal is approximately 17 380 kJ/kg.

It has been established that the content of coke breeze in the briquette composition significantly increases the lower calorific value. Obviously, this is explained by the high heat of combustion of coke dust (26 000 kJ/kg).

The maximum calorific value (24 479.7 kJ/kg) was established for a briquette made from 30 % sunflower cake and 70 % coke breeze. The minimum value of the lower calorific value (19 761.3 kJ/kg) was found for a briquette made of 70 % buckwheat husk and 30 % coke breeze. This is explained by the lower heat of combustion of buckwheat (17 000 kJ/kg) relative to other used plant waste.

Figures 3.45 – 3.48 show the results of determining the lower calorific value of briquettes from sunflower husks (fine fraction), sunflower cake and buckwheat husks, depending on the ratio in the mixture.

Figure 3.45 shows the results of determining the lower calorific value of briquettes made from sunflower husks and coke dust. The lower calorific value of these types of briquettes varies from 24 4479.7 kJ/kg to 21 391.3 kJ/kg. A decrease in the lower calorific value of a briquette made from sunflower husks and coke breeze occurs with a decrease in the composition of coke dust.

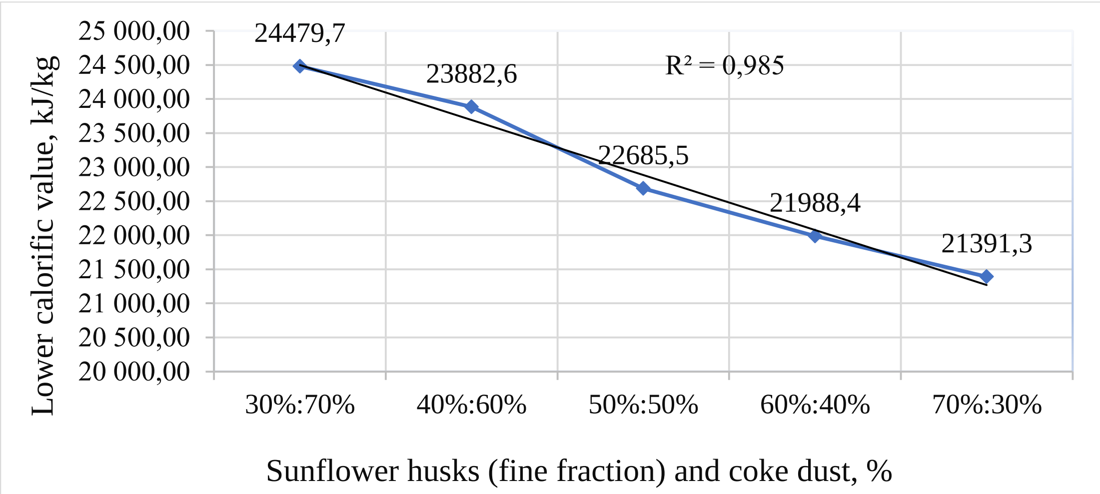


Figure 3.45 – Lower calorific value of briquettes made from sunflower husks and coke dust

Moreover, this dependence is linear

$$y = -807.1 \cdot x + 25307. \quad (3.34)$$

The results of determining the lower calorific value of briquettes made from sunflower cake and coke dust are presented in Figure 3.46. It can be stated that this parameter has good values. The lower calorific value ranges from 24931.8 kJ/kg to 22346.2 kJ/kg. With a decrease in the proportion of coke dust in the composition, the lower calorific value of the combined briquette decreases.

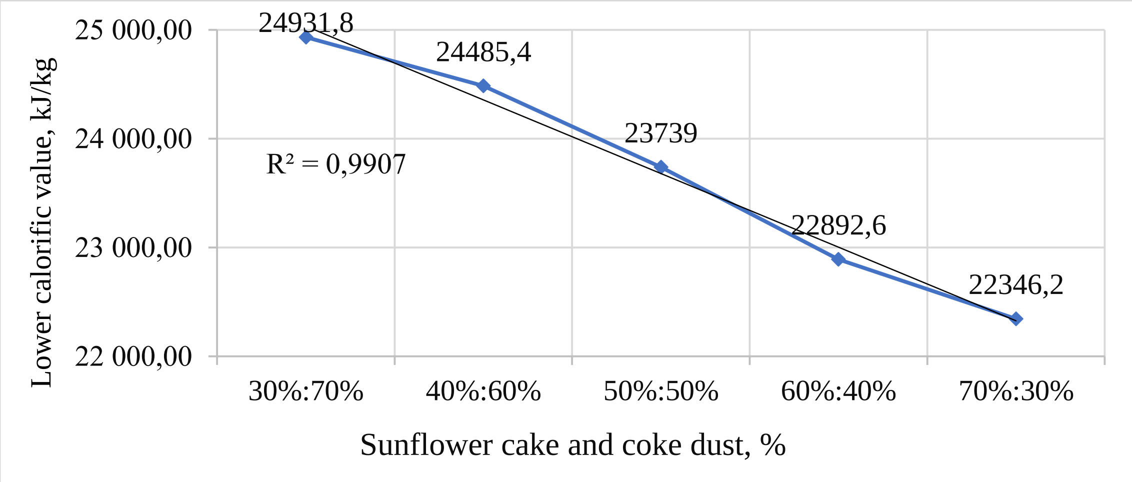


Figure 3.46 – Lower calorific value of briquettes made from sunflower cake and coke dust

The approximation of the obtained dependence shows its linear nature

$$y = -646{,}4 \cdot x + 25708. \quad (3.35)$$

Figure 3.47 presents the results of a study to determine the lower calorific value of briquettes made from buckwheat husks and coke dust. They indicate that, as in previous cases, the decrease in the heat of combustion is associated with a decrease in coke dust in its composition. The lower calorific value of a briquette varies from 23909.7 kJ/kg to 19761.3 kJ/kg.

The resulting dependence is linear

$$y = -1067{,}1 \cdot x + 25237. \quad (3.36)$$

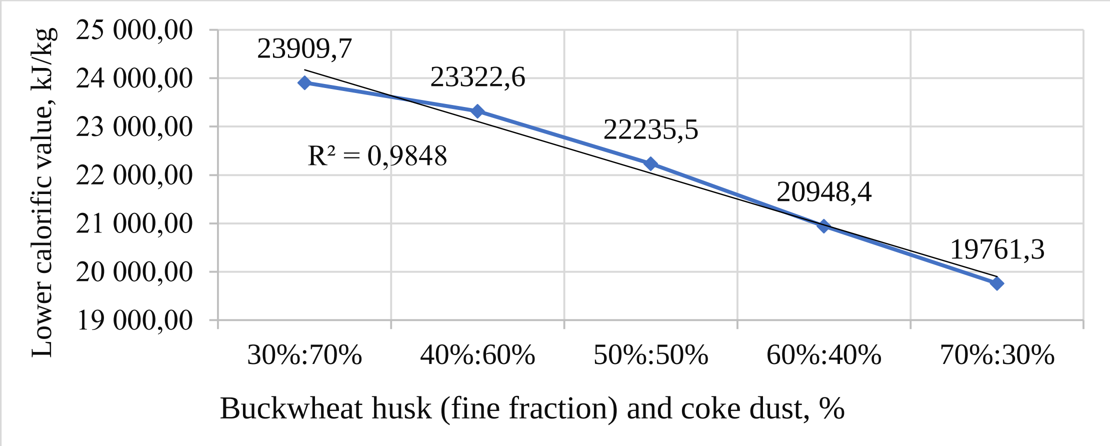


Figure 3.47 – Lower calorific value of briquettes made from buckwheat husks and coke dust

During the comparative analysis, the nature of the change in the calorific value of briquettes was studied depending on the ratio between the components (figure 3.48).

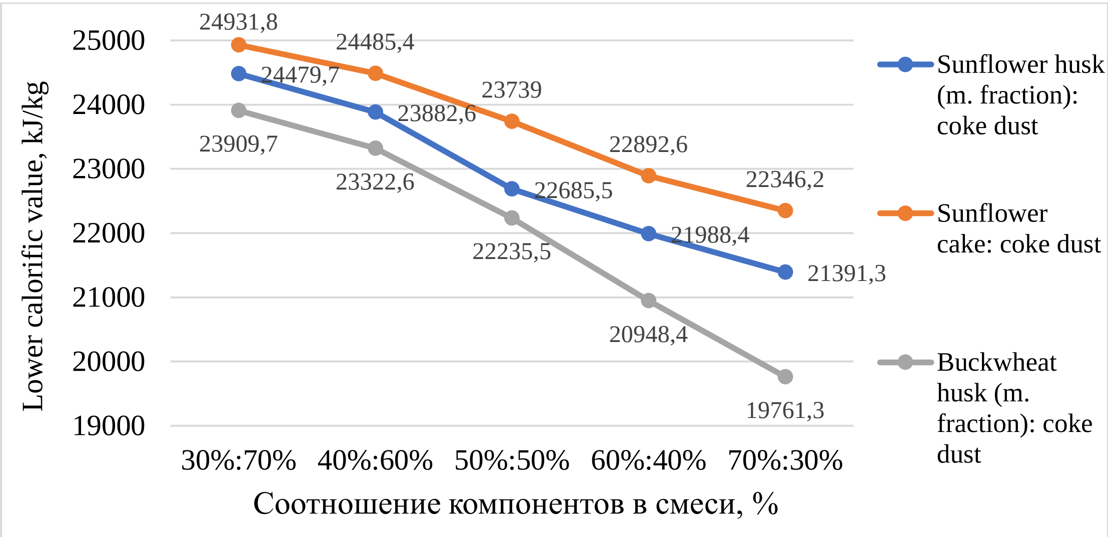


Figure 3.48 – Dependence of the calorific value of briquettes on the ratio of components in the mixture

It is known that coconut dust, as a product of oil calcination of coke, has a high calorific value (26 MJ/kg). Analysis of the relationship presented in figure 3.48 showed that the content of coke breeze in the composition of the fuel briquette has a positive effect on its calorific value. The lower heating value increases significantly. Among the used organic waste, buckwheat husk has the lowest calorific value. Therefore, the heat of combustion of briquettes containing buckwheat husks is lower than that of other mixtures.

3.3 Comparative analysis of thermal characteristics of fuel briquettes

Let us conduct a comparative analysis of the thermal characteristics of the resulting briquettes. The purpose of this analysis is to determine briquettes with the best parameters in terms of strength, moisture, ash content and calorific value.

The thermal characteristics of combined fuel briquettes from agricultural and industrial waste determined in this way are presented in tables 3.3 – 3.9.

Table 3.3 – Thermal characteristics of briquettes made from buckwheat husks (large fraction) and sunflower husks

Sample		Density, kg/m^3	Strength, %	Humidity, %	Ash, %	Volatile yield, %	Lower calorific value. kJ/kg
	Buckwheat husk (large fraction): sunflower husk (30 %:70 %)	1228,35	79,92	4,50	3,65	81,27	18421,7
	Buckwheat husk (large fraction): sunflower husk (40 %:60 %)	1211,11	76,40	4,87	3,50	81,15	18138,6
	Buckwheat husk (large fraction): sunflower husk (50 %:50 %)	1056,13	73,20	5,13	3,40	79,77	18015,5
	Buckwheat husk (large fraction): sunflower husk (60 %:40 %)	844,64	69,05	5,3	3,30	77,60	17812,4
	Buckwheat husk (large fraction): sunflower husk (70 %:30 %)	789,58	66,48	5,50	3,00	76,20	17509,3

A comparative analysis of the characteristics of bricks made from sunflower husks and buckwheat husks (large fraction) makes it possible to draw the following conclusions. Despite the good values of humidity, ash content, volatile yield and calorific value, most of the briquettes of this type have low density and strength. Density and strength are the most important parameters that determine the suitability of a briquette for transportation and resistance to external mechanical influences. It is the strength that determines the feasibility of making a briquette in principle. During the comparative analysis, the best brique of this type was selected. It is a briquette made of 30% buckwheat husk and 70 % sunflower husk with the following parameters: humidity 4.50%, ash content 3.65 %, volatile yield 81.27 %, strength 79.92 %, density 1228.35 kg/m^3, lower calorific value 18421.7 kJ/kg.

Table 3.4 – Thermal characteristics of briquettes made from buckwheat husks (fine fraction) and leaves

Sample		Density, kg/m^3	Strength, %	Humidity, %	Ash, %	Volatile yield, %	Lower calorific value. kJ/kg
	Buckwheat husk (fine fraction): leaves (30 %:70 %)	1252,93	90,78	4,16	5,40	59,16	19844,2
	Buckwheat husk (fine fraction): leaves (40 %:60 %)	1236,77	88,56	4,50	5,00	60,21	19323,6
	Buckwheat husk (fine fraction): leaves (50 %:50 %)	1202,23	85,37	4,80	4,60	62,73	19103
	Buckwheat husk (fine fraction): leaves (60 %:40 %)	1179,58	82,49	5,00	4,00	65,26	18582,4
	Buckwheat husk (fine fraction): leaves (70 %:30 %)	1067,02	80,54	5,40	3,86	67,15	18241,8

All briquettes made from buckwheat husks and sunflower husks have high strength and density. The values of humidity, ash content, volatile yield and calorific value meet the requirements. However, it is worth noting that briquettes with a large proportion of buckwheat husk in their composition are vulnerable to mechanical stress.

Based on the above, two samples with the best characteristics for this type of briquettes were selected. They are: 1) briquette of 40% buckwheat husk and 60 % leaves with the following parameters: humidity 4.50 %, ash content 5.00 %, volatile yield 60.21 %, strength 88.56 %, density 1236.77 kg/m^3, lower calorific value 19323.6 kJ/kg; 2) briquette of 30 % buckwheat husk and 70 % leaves with the following parameters: humidity 4.16 %, ash content 5.40 %, volatile yield 59.16 %, strength 90.78 %, density 1252.93 kg/m^3, lower calorific value 19844.2 kJ/kg.

Table 3.5 – Thermal characteristics of briquettes made from sunflower leaves and husks.

Sample		Density, kg/m^3	Strength, %	Humidity, %	Ash, %	Volatile yield, %	Lower calorific value. kJ/kg
	Leaves: sunflower husk (30 %:70 %)	1038,92	81,75	3,62	3,50	73,30	19583,5
	Leaves: sunflower husk (40 %:60 %)	1050,53	82,89	3,59	4,00	73,06	19931,0
	Leaves: sunflower husk (50 %:50 %)	1103,54	83,03	3,50	4,43	70,98	20168,5
	Leaves: sunflower husk (60 %:40 %)	1290,00	86,05	3,48	4,82	63,73	20306,0
	Leaves: sunflower husk (70 %:30 %)	1358,81	91,80	3,39	5,23	62,30	20553,5

A comparative analysis of the characteristics of briquettes made from sunflower husks and leaves showed that all ratios of the mixture composition in this briquette have good values. The obtained characteristics (density, strength, humidity, ash content, volatile yield, calorific value) correspond to the existing requirements for briquettes. However, it is worth noting that samples with a large proportion of sunflower husks are not strong enough due to their oiliness. This negatively affects mechanical stability. The strength of these briquettes will increase with increasing proportion of leaves in the briquette. The leaves contain a natural binder – lignin.

Based on the analysis, the most durable briquette was selected from 70% leaves and 30 % sunflower husk with the following parameters: humidity 3.39 %, ash content 5.23 %, volatile yield 62.30 %, strength 91.80 %, density 1358 .81 kg/m^3, lowest calorific value 20 533.5 kJ/kg.

Table 3.6 – Thermal characteristics of briquettes made from sunflower husks (fine fraction) and coke breeze

Sample		Density, kg/m^3	Strength, %	Humidity, %	Ash, %	Volatile yield, %	Lower calorific value. kJ/kg
	Sunflower husks (fine fractions): coke breeze (30 %:70 %)	897,38	56,28	1,99	6,25	26,65	24479,7
	Sunflower husks (fine fractions): coke breeze (40 %:60 %)	943,29	57,32	2,61	5,23	31,99	23882,6
	Sunflower husks (fine fractions): coke breeze (50 %:50 %)	957,24	63,61	3,31	2,44	44,00	22685,5
	Sunflower husks (fine fractions): coke breeze (60 %:40 %)	976,81	74,60	3,75	1,99	53,71	21988,4
	Sunflower husks (fine fractions): coke breeze (70 %:30 %)	1009,27	83,45	4,06	1,35	56,68	21391,3

Table 3.6 presents a comparative analysis of the characteristics of bricks made from sunflower husks (fine fraction) and coke breeze (dust). It can be noted that briquettes containing 50 percent or more coke dust have low density and strength. This can be explained by poor adhesion of the mower dust to the components of the mixture. Coke dust has a fine structure and low humidity. There are no binding elements in the composition of coke dust. In addition, coke dust significantly increases the ash content of the final briquette. Thus, the low strength of such briquettes makes their production inappropriate. Despite the high heat of combustion and low humidity, the determining criterion in this case will be strength.

Taking into account the analysis, the best briquette in this series was selected. This is a sample of 70% sunflower husk and 30 % coke dust. It has the following parameters: humidity 4.06 %, ash content 1.35 %, volatile yield 56.68 %, strength 83.45%, density 1009.27 kg/m^3, lower calorific value 21391.3 kJ/kg. In addition to high density and strength, this sample has the lowest ash content and high volatile yield.

Table 3.7 – Thermal characteristics of briquettes made from sunflower cake and coke breeze

Sample		Density, kg/m^3	Strength, %	Humidity, %	Ash, %	Volatile yield, %	Lower calorific value. kJ/kg
	Cake: coke breeze (30 %:70 %)	1052,33	60,56	1,64	6,76	18,04	24931,8
	Cake: coke breeze (40 %:60 %)	1076,84	81,71	1,79	4,91	26,01	24485,4
	Cake: coke breeze (50 %:50 %)	1182,39	96,19	1,96	4,00	32,36	23739
	Cake: coke breeze (60 %:40 %)	1294,31	99,56	2,50	3,03	46,15	22892,6
	Cake: coke breeze (70 %:30 %)	1337,14	99,63	3,00	2,86	55,73	22346,2

The characteristics presented in table 3.7 have been carefully analyzed. The analysis showed that with an increase in the proportion of sunflower cake, the strength of the briquettes increases. The increased content of oil components in sunflower cake and a small proportion of lignin make it possible to firmly bind the fractions of coconut dust and cake to each other. Therefore, from the point of view of strength, briquettes with a high content of cake appear to be the most optimal.

Based on the comparative analysis, two samples were selected: 1) briquette of 70 % cake and 30 % coke dust with the following parameters: humidity 3.00 %, ash content 2.86 %, volatile yield 55.73 %, strength 99.63 % , density 1337.14 kg/m^3, lower calorific value 22346.2 kJ/kg; 20 briquettes of 60 % cake and 40% coke dust with parameters: humidity 2.50 %, ash content 3.03 %, volatile yield 46.15 %, strength 99.56%, density 1294.31 kg/m^3, lower calorific value 22892.6 kJ/kg. The selected briquettes are characterized by high density and strength, low humidity, low ash content, high yield of volatile substances, and high calorific value.

Table 3.8 – Thermal characteristics of briquettes made from buckwheat husks (fine fraction) and coke dust

Sample		Density, kg/m^3	Strength, %	Humidity, %	Ash, %	Volatile yield, %	Lower calorific value. kJ/kg
	Buckwheat husk (m. fraction): coke breeze (30 %:70 %)	1101,68	45,12	3,00	5,50	29,74	23909,7
	Buckwheat husk (m. fraction): coke breeze (40 %:60 %)	1123,82	53,67	3,58	5,20	37,76	23322,6
	Buckwheat husk (m. fraction): coke breeze (50 %:50 %)	1148,47	66,42	4,00	4,80	40,31	22235,5
	Buckwheat husk (m. fraction): coke breeze (60 %:40 %)	1156,79	72,06	4,52	4,20	47,62	20948,4
	Buckwheat husk (m fraction): coke breeze (70 %:30 %)	1164,55	75,91	5,00	4,00	51,04	19761,3

These characteristics (table 3.8) were analyzed. The studied samples showed an increased ash content and a low volatile yield. In terms of strength, all samples are easily damaged and do not have good mechanical strength. Thus, despite the good thermal characteristics of briquettes of this composition, their further use is inappropriate

Based on the analysis of tables 3.3 – 3.8, briquettes were identified that fully meet the quality requirements (table 3.9). These include briquettes made only from plant materials and briquettes with the addition of industrial waste.

Table 3.9 – Summary table of briquettes with the best thermal characteristics

Sample		Density, kg/m^3	Strength, %	Humidity, %	Ash, %	Volatile yield, %	Lower calorific value. kJ/kg
	Buckwheat husk (red fraction): sunflower husk (30 %:70 %)	1228,35	79,92	4,50	3,65	81,27	18461,7
	Buckwheat husk (m. fraction): leaves (30 %:70 %)	1252,93	90,78	4,16	5,40	59,16	19844,2
	Buckwheat husk (m. fraction): leaves (40 %:60 %)	1236,77	88,56	4,50	5,00	60,21	19323,6
	Leaves: sunflower husk (70 %:30 %)	1358,81	91,80	3,39	5,23	62,30	20553,5
	Sunflower husk (m. fraction): coke breeze (70 %:30 %)	1009,27	83,45	4,06	1,35	56,68	21391,3

continuation of table 3.9

	Cake: coke breeze (50 %:50 %)	1182,39	96,19	1,96	4,00	32,36	23739
	Sunflower cake: coke breeze (60 %:40 %)	1294,31	99,56	2,50	3,03	46,15	22892,6
	Sunflower cake: coke breeze (70 %:30 %)	1337,14	99,63	3,00	2,86	55,73	22346,2

Based on the characteristics of the briquettes (table 3.9), we can conclude that most of these briquettes have good thermal characteristics. The selection of the best samples will be made on the basis of strength characteristics. Thus, the best examples are the following briquettes:

- buckwheat husk (fine fraction) and leaves (30%:70%);
- sunflower leaves and husks (70%:30%);
- sunflower cake and coke breeze (50%:50%);
- sunflower cake and coke breeze (60%:40%);
- sunflower cake and coke breeze (70%:30%).

An assessment of the characteristics of briquettes made from agricultural waste showed the following:

- density is in the range from 790.00 to 1358.81 kg/m^3;
- strength is in the range from 66.48 to 91.80 %;
- moisture content is in the range from 3.39 to 5.50 %;
- ash content is in the range from 3.00 to 5.40 %;
- the yield of volatiles is in the range from 59.16 to 81.27 %;
- calorific value is in the range from 17.00 to 20.50 MJ/kg.

Analysis of the thermal characteristics of briquettes made from organic and industrial waste showed the following:

- density is in the range from 897.38 to 1337.14 kg/m^3;
- strength is in the range from 45.12 to 99.63 %;
- moisture content is in the range from 1.64 to 5.00 %;
- ash content is in the range from 1.35 to 6.76 %;
- the yield of volatiles is in the range from 18.04 to 56.68 %;
- calorific value is in the range from 19.96 to 24.93 MJ/kg.

It should be noted that the moisture level in briquettes made from agricultural and industrial waste increases with increasing proportion of plant raw materials.

The yield of volatile substances will be significantly higher for briquettes made from plant waste (from 59.16 to 81.27 %) than for samples with the addition of coke dust (from 18.04 to 56.68 %).

The density of combined fuel briquettes will increase as they grow in the composition of plant raw materials.

A comparative analysis of the thermal characteristics of briquettes made it possible to determine briquettes with the best parameters in terms of strength, moisture, ash content and calorific value:

- 30 % buckwheat husk (fine fraction) and 70 % leaves;
- 70 % leaves and 30 % sunflower husks;
- 50 % sunflower cake and 50 % coke dust;
- 60 % sunflower cake and 40 % coke dust;
- 70 % sunflower cake and 30 % coke dust.

4 Study of the influence of the fractional composition of fuel briquettes on the calorific value

4.1 Planning and conducting the experiment

From a general philosophical point of view, experiment (from Latin experimentium – test, experience) is a sensory-objective activity in science. In a narrower sense of the word, an experiment is an experience, reproduction of an object of study, testing of hypotheses, etc. [54].

Most scientific research involves experimentation. Recently, along with physical models, computer models are increasingly being used, on which one can perform simulation experiments and obtain new information about the object of study.

It is known that when studying simple objects, it is enough to conduct a one-factor experiment. With the increasing complexity of the research object, a need arose to improve experimental research. The experiment itself became a complex object of study.

Despite the fact that the objects of research are very diverse, all methods of experimental research have much in common:

● any experiment (simple or complex) must begin with planning;

● to reduce the volume of an experiment, researchers always strive to reduce the number of input factors being studied;

● Researchers always try to control the progress of the experiment and exclude the influence of random external factors.

Experimental planning is a branch of mathematical statistics that studies the rational organization of measurements and observations [55].

Experimental planning consists of the procedure for selecting the number and conditions for conducting experiments necessary and sufficient to study an object with a given accuracy.

Planning an experiment makes it possible [56]:

● simultaneous change of all factors according to special rules;

● use of mathematical apparatus to formalize the actions of the experimenter;

● choose a clear strategy that allows you to make informed decisions after each series of experiments;

● minimize the number of experiences, resources (financial, temporary, material, human).

The construction of empirical models is based on the theory of multifactor experiment (MFE), developed by R. Fischer in the 30s. XX century Fisher's theory is based on the study of the behavior of the object of study while simultaneously changing several input factors.

It is known that according to the form of conducting and presenting the results, experiments can be qualitative or quantitative [55]. A qualitative experiment establishes the very fact of the existence of an object, process or phenomenon, but does not provide any quantitative characteristics. A quantitative experiment not only records the very fact of the existence of a particular object, process or phenomenon, but also makes it possible to establish a relationship between the quantitative characteristics of the behavior of the object under study and the quantitative characteristics of external influence.

A factor is a variable quantity that at each moment of time takes on a certain value from its domain of definition and reflects an external influence on an object or its response to this influence. Factor level is a specific value of a factor from its domain of definition during an experimental study of an object.

When conducting experiments, an important point is to determine the levels of factors that are of interest to the researcher. The following types of factors are distinguished [55]:

- controlled and manageable – these are factors for which you can not only determine their level, but also set any possible value in each experiment;
- controlled, but not controllable – these are factors whose levels can only be recorded, but it is almost impossible to set a certain value in each experiment;
- uncontrollable – these are factors whose levels are not recorded by the researcher; he may not even be aware of their existence.

If the researcher has the ability to control and manipulate the levels of factors, then such an experiment can be considered active. If the researcher can only observe and record, but has no ability to control factor levels, then it is a passive experiment.

During an experimental study, the object is viewed as a «black box» (figure 4.1). The output factors in the experiment are called the response, and the dependence $Yj = f(X_1, X_2, \dots X_k)$, which they are trying to establish, is the response function.

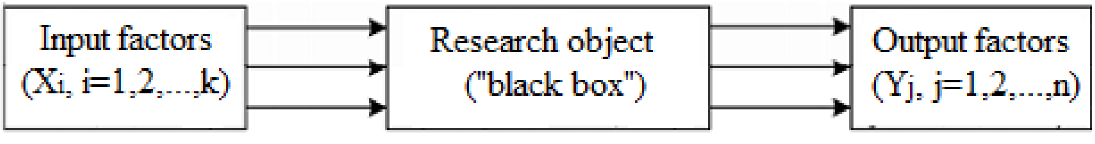


Figure 4.1 – Object of study in general form

Thermal technological processes are very complex in their physical and chemical nature. There are still no universally accepted analytical models that accurately describe the patterns of various thermo-technological processes, especially thermal processes, etc. Therefore, empirical models are very often used. Empirical models are the result of processing experimental data on the behavior of an object or process using methods of mathematical statistical analysis.

Very often, to build models of objects based on the results of experimental studies, the mathematical apparatus of regression and correlation analysis is used.

4.2 Problem statement

An objective indicator of a high-quality briquette is its calorific value, namely the lower calorific value. It is directly related to such characteristics of briquettes as humidity, ash content and the content of combustible elements in the mixture.

This dependence can be considered random and analyzed using probabilistic methods. For effective analysis, it is necessary to identify the relationships between input factors and present them in quantitative form – in the form of a mathematical model

$$\sigma = \sigma(x_1, x_2, ..., x_n), \tag{4.1}$$

where σ – the strength of briquettes, %;

x ,x ,…,x – factors influencing the lower calorific value.

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

From physical considerations we can assume that the relationship between expression (4.1) has the following form

$$\sigma(b,x) = b_0 + \sum_{i=1}^{n} b_i x_i \ , \tag{4.2}$$

where b_0– is the free term equal to the output at x=0;

b_i – regression coefficient.

We select as experimental factors: x_1 – briquette humidity, %; x_2 – ash content of the briquette, %; x_3 – content of combustible elements in the briquette, %.

Having determined the regression coefficients of this equation, we will get an idea of the influence of the factors under study on the value of the net calorific value of the briquette. Regression coefficients are calculated using the following formulas [57]

$$b_i = \frac{1}{N}\sum_{j=1}^{N}\bar{\sigma}_j x_i^j,\ i = 0,..,n,$$
$$b_{ij} = \frac{1}{N}\sum_{j=1}^{N}\bar{\sigma}_j x_i^j..x_{\mu}^j, i, \mu = 1,2,..,n, \quad (4.3)$$

where $\bar{\sigma}_j$ is the value of the average output of the process in the j-th variant;

x_i^j – the value of the factor in the j-th variant.

To assess the significance of regression coefficients, it is necessary to find their sample variance $S^2[b_i]$. The significance of regression coefficients is determined by the inequality

$$b_i \succ S[b_i]\cdot t_p(f), \quad (4.4)$$

where $t_p(f)$ is the Student coefficient for a given reliability p and the number of degrees of freedom $f = (\nu - 1)\cdot N$.

Thus, the mathematical model of this process can be described quite accurately using the interpolation formula (4.2), taking into account the assessment of the influence of each of the experimental factors on the target value.

4.3 Simulation results

Two experiments were carried out at each experimental point. To calculate coefficient estimates, the arithmetic mean of these observations for each point was used. Next, based on experimental data, coefficient estimates were calculated using formulas (4.3). Thus, the form of interpolation formula (4.2) is obtained. The last stage was to assess the significance of the regression coefficients and check the adequacy of the model.

Using the above methodology, we determine the regression coefficients of the equation for manufactured fuel briquettes from organic mass. Table 4.1 shows the experimental plan to study the influence of various factors on the calorific value of biochar briquettes made from sunflower husks and coal dust (Karazhyra) and its results. The process yield values were obtained as a result of experimental studies.

Table 4.1 – Experiment planning matrix

Experiment number	Planning				Lower calorific value, kJ/kg
	x_0	x_1	x_2	x_3	
1	+	+	+	+	24675,23
2	+	-	+	+	25703,86
3	+	+	-	+	26689,98
4	+	-	-	+	27948,49
5	+	+	+	-	18663,74
6	+	-	+	-	19463,87
7	+	+	-	-	20303,61
8	+	-	-	-	21166,83

Based on the resulting experiment planning matrix, the regression coefficients of equation (4.2) were determined. The regression formula for the dependence of the calorific value of briquettes on the parameters of the briquettes took the following form

$$\hat{\sigma} = 23076{,}95 - 493{,}81x_1 - 950{,}27x_2 + 3177{,}44\,x_3. \qquad (4.5)$$

The analysis of dependence (4.5) revealed that the factor x_3 (the combustible component, that is, the ratio of husk and coal dust in the initial briquetting mass) has the greatest influence on the value of the calorific value. The heat of combustion is least affected by humidity.

Let us check the adequacy of the model and the significance of quadratic effects in both experiments.

For a given significance level of testing the hypothesis of adequacy, $\alpha = 0.05$ in accordance with the 95% F-distribution $F_{cr} = 5.32$. In our case, $F_1 = 2{,}29 < F_{кр} = 5{,}32$ and $F_2 = 1{,}00 < F_{кр} = 5{,}32$. Thus, the adequacy check showed that the proposed models are adequate, because errors characterizing the accuracy of models do not exceed observational errors.

To assess the significance of regression coefficients, it is necessary to find their sample variance $S^2[b_l]$. The significance of the regression coefficients is determined by the inequality $b_l \succ S[b_l]\cdot t_p(f)$, where $t_p(f)$ is the Student coefficient for a given reliability p and the number of degrees of freedom $f = (\nu - 1)\cdot N$.

Testing the significance of the coefficients showed that all coefficients of these models are significant. Consequently, regression equations (4.5), taking into account this remark, will remain in the same form.

In a similar way, regression dependencies were obtained for other types of briquettes. All simulation results are summarized in table 4.2.

Table 4.2 – Results of modeling the influence of thermal parameters of biochar briquettes on the lower calorific value

Вид брикета	Регрессионная зависимость
Sunflower husk + coal dust (Karazhyra)	$\hat{\sigma} = 23076{,}95 - 493{,}81x_1 - 950{,}27x_2 + 3177{,}44\, x_3$
Sunflower husk + coal dust (Shubarkul)	$\hat{\sigma} = 23661{,}51 - 291{,}45x_1 - 681{,}48x_2 + 3419{,}34\, x_3$
Sunflower husk + coke dust	$\hat{\sigma} = 22273{,}92 - 105{,}80x_1 - 218{,}54x_2 + 1849{,}72\, x_3$
Leaves + coal dust (Karazhyra)	$\hat{\sigma} = 24461{,}98 - 647{,}89x_1 - 916{,}87x_2 + 2578{,}66\, x_3$
Leaves + coal dust (Shubarkul)	$\hat{\sigma} = 24270{,}91 - 294{,}67x_1 - 424{,}81x_2 + 3022{,}03\, x_3$

Analysis of the obtained dependencies showed the same nature of the influence of the thermal characteristics of biochar briquettes on their calorific value. The factor x_3 (combustible component, that is, the ratio of husk and coal dust in the initial briquetting mass) has the greatest influence on the value of the heat of combustion. The heat of combustion is least affected by humidity (two times less than the ash content).

Conclusion

In the course of the study, a review of foreign literary sources was carried out, which examined technologies for the production of fuel briquettes from raw materials of plant and industrial origin, as well as their thermal characteristics established in laboratory conditions.

An analysis of Kazakhstan's raw material base for plant waste shows that the country has a fairly developed agro-industrial complex and has a sufficient number of cultivated grain and oilseed crops, the waste of which is not properly disposed of.

The analysis of the characteristics of plant and industrial waste showed that plant waste has good thermal parameters, allowing them to be used as raw material for the production of briquettes. They are characterized by low humidity and ash content up to 10 %, high volatile yield over 60% and good calorific value from 15 to 21 MJ/kg. Industrial waste, in this case coke dust, despite its high ash content and low volatile yield, has a high calorific value of 26 MJ/kg.

In laboratory conditions, by pressing under a pressure of 25 MPa, fuel briquettes weighing 10 g were produced without the use of binders with different percentages of raw materials in the composition. The raw materials for the production of briquettes were the following waste: buckwheat husks, sunflower husks and cake, coke breeze. During manufacturing, by mixing various raw materials with each other, the most suitable combination of raw materials in the briquette was determined:

- mixing leaves with their content in a mixture of more than 50% with any of the waste considered (sunflower husks and cake, buckwheat husks and coke dust) allows you to obtain strong and durable briquettes;
- mixing sunflower cake, with its content in the mixture above 50%, with coke dust, due to the oiliness of the former, allows you to obtain a durable briquette and facilitate the pressing process.

The study determined the thermal characteristics of manufactured fuel briquettes from plant waste:

- humidity ranges from 3.39 to 5.50 %;
- ash content ranges from 3.00 to 5.40 %;
- the yield of volatiles ranges from 59.16 to 81.27 %;
- density ranges from 789.58 to 1358.81 kg/m^3;
- strength ranges from 66.48 to 91.80 %;
- calorific value ranges from 17.60 to 20.55 MJ/kg.

Thermal characteristics of briquettes made from plant and industrial waste:

- humidity ranges from 1.64 to 5.00 %;

- ash content ranges from 1.10 to 9.50 %;
- the yield of volatiles ranges from 18.04 to 56.68 %;
- density ranges from 897.38 to 1337.14 kg/m^3;
- strength ranges from 45.12 to 99.63 %;
- calorific value ranges from 19.96 to 24.93 MJ/kg.

Most of the resulting briquettes have good performance in terms of moisture and ash content, and calorific value. However, high strength was detected in a small number of samples.

As a result of a comparative analysis of thermal characteristics between briquettes from plant and industrial waste, the best samples were selected in terms of thermal parameters and their compliance with the requirements [34], [35]:

- 30 % buckwheat husk (fine fraction) and 70 % leaves with the following parameters: humidity – 4.16 %, ash content – 5.40 %, calorific value – 19.8 MJ/kg, strength – 90.78 %;
- 70 % leaves and 30 % sunflower husk with the following parameters: humidity – 3.39 %, ash content – 5.23 %, calorific value – 20.5 MJ/kg, strength – 91.80 %;
- 50 % sunflower cake and 50 % coke breeze with the following parameters: humidity – 1.96 %, ash content – 4.00 %, calorific value – 23.7 MJ/kg, strength – 96.19 %;
- 60 % sunflower cake and 40 % coke breeze with the following parameters: humidity – 2.50 %, ash content – 3.03 %, calorific value – 22.8 MJ/kg, strength – 99.56 %;
- 70 % sunflower cake and 30 % coke breeze with the following parameters: humidity – 3.00 %, ash content – 2.86 %, calorific value – 22.3 MJ/kg, strength – 99.63 %.

While simulating the briquetting process:

- regression dependencies were obtained estimating its heat of combustion;
- an analysis of the obtained dependencies was carried out, the significance of the coefficients included in the model was checked;
- the strength of the briquette is most influenced by the combustible component, that is, the ratio of husks and coal dust in the initial briquetting mass;
- the heat of combustion is least affected by humidity;
- the adequacy of these models was checked, which showed that the proposed models are adequate, because errors characterizing the accuracy of the model do not exceed observational errors.

Reference

1 Страны лидеры по добыче и запасам угля в мире [Электронный ресурс] - https://tyulyagin.ru.

2 Список стран по добыче природного газа [Электронный ресурс] - https://ru.wikipedia.org/wiki.

3 Список стран по добыче нефти [Электронный ресурс] - https://ru.wikipedia.org.

4 Выбросы CO_2 в Казахстане по видам топлива [Электронный ресурс] - https://ourworldindata.org.

5 Солодов В. С. Разработка технологии утилизации коксовой пыли коксохимических производств в виде брикетов повышенной прочности / В. С. Солодов, А. В. Папин, Т. Г. Черкасова // Ползуновский вестник. – 2011. – № 4-2. – С. 159-164.

6 Статистический отдел Европейской экономической комиссии ООН Кабинетное исследование об Оценке потенциала стран Восточной Европы, Кавказа и Центральной Азии в области разработки статистических данных для измерения устойчивого развития и экологической устойчивости от Организации Объединенных Наций [Электронный ресурс]. – 2012. https://unece.org/fileadmin/DAM/stats/documents/ece/ces/ge.33/2013/mtg2/SD_desk_study_RU_Final.pdf.

7 Кравцов В. П. Актуальность технологии брикетирования коксовой пыли / В. П. Кравцов, А. В. Папин // Вестник КузГТУ. – 2012. – № 4. – С. 112–114.

8 Егоров А. Н. Отходы нефтехимических производств – сырьё для ресурсосберегающих технологий: учебное пособие / А. Н. Егоров, Г. И. Егорова // – Тюмень : ТИУ. – 2016. –190 с.

9 Хараз Д. И. Пути использования вторичных энергоресурсов в химических производствах. – М. : Химия, 1984. – 224 с.

10 ЕБРР Биоэнергетический потенциал в агропромышленном секторе Казахстана [Электронный ресурс] - www.ebrd.com.

11 Информация о сокращении, переработке и вторичном использовании отходов [Электронный ресурс] - https://egov.kz/cms/ru/articles/ecology/waste_reduction_recycling_and_reuse.

12 Судакова И. Г., Руденко Н. Б. Получение твердых биотоплив из растительных отходов (обзор) // Журнал Сибирского федерального университета. Серия: Химия. – 2015. – № 4. – С.499-513.

13 Характеристики биомассы, как энергетического топлива [Электронный ресурс] - http://www.gigavat.com/netradicionnaya_energetika_biomassa_4.php

14 Осьмак А. А., Серегин А. А.. Растительная биомасса как органическое топливо // Восточно-Европейский журнал передовых технологий. – Киев, 2014.

15 Kpalo SY, Zainuddin MF, Halim HBA, Ahmad AF, Abbas Z. Physical characterization of briquettes produced from paper pulp and Mesuaferrea mixtures // Biofuels. – 2019. 1–8 p.

16 Kpalo SY, Zainuddin MF, Manaf LA, Roslan AM. Production and Characterization of Hybrid Briquettes from Corncobs and Oil Palm Trunk Bark under a Low-Pressure Densification Technique // Sustainability. – 2020.

17 S. Suryaningsih, O. Nurhial, Y. Yuliah. Combustion quality analysis of briquettes from variety of agricultural waste as source of alternative fuels // IOP Publishing. – Indonesia, 2017. – № 65.

18 W. Anggono, Sutrisno, D. Fandi. Biomass Briquette Investigation from Pterocarpus Indicus Leaves Waste as an Alternative Renewable Energy // IOP Publishing. – Indonesia, 2017.

19 I. Ikelle, J. Nworu, F. Nworie. Thermal Analyses of Briquette Fuels Produced from Coal Dustand Groundnut Husk // ACMY. – Nigeria, 2020.

20 W. Suwinarti, R. Amirta. Production of high-calorie energy briquettes from bark waste, plasticand oil // IOP Publishing. – Indonesia, 2018. – № 144.

21 Жанабаев А. Ж., Шаймерденова Д. А., Омаров К. К., Чаканова Ж. М, Кокумбекова Н. К. Патент Республики Казахстан №25747. Топливный брикет из отходов шелушения зерна овса. - опубл. 15.05.2012.

22 Папин А. В. Получение топливных брикетов из тонкодисперсных отходов угледобычи и углепераработки / А. В. Папин, А. Ю. Игнатова, А. В. Неведров, Т. Г. Черкасова // Вестник КузГТУ. – 2015. – № 5. – С. 45–49.

23 А. В. Папин. Экологические и технологические аспекты утилизации коксовой пыли в виде топливных брикетов / А. Ю. Игнатова, В. С. Солодов // КузГТУ имени Т. Ф. Горбачева. – 2013. – № 2. – С. 66–70.

24 Н. В. Бардашова. Исследование топливных характеристик брикетного образца / Н. В. Бардашова, Е. Г. Беккер // Современные техника и технологии: сборник трудов XVII Международная научно-практическая конференция. – Томск, 2011. – Т.3. – С. 189-190.

25 Тунцев Д. В., Харьков В.В., Кузнецов М. Г. Переработка лузги подсолнечника в угольные брикеты высокой прочности // Вестник Казанского ГАУ. – 2019. – № 4(56).

26 Желтунов М. Г., Куркин С. С. Патент 2524032 Российская Федерация. Брикетный штемпельный пресс. – опубл. 27.07.2014.

27 Яблокова М. А., Пономаренко Е. А., Георгиевский Н. В. Современные технологии и оборудование для утилизации мелких нетоварных фракций нефтяного кокса (обзор)// Химия и химическая технология. Процессы и аппараты. Известия СПбГТИ(ТУ). – 2016. –№34.

28 Шашмурин П. И., Андрейков Е. И., Посохов М. Ю. Патент 2375414 Российская Федерация. Способ изготовления брикетного топлива. – опубл. 10.12.2009.

29 Лугань Топ Сервис. Оборудование для производства брикетов из угольной пыли, шлама и других материалов без связующих веществ. [Электронный ресурс] - https://lugantopservice.com.ua/.

30 Charcoal briquette extruding machine (машина для экструзионного брикетирования угольной пыли). [Электронный ресурс] - https://www.oltencharcoalmachine.com.

31 ЕБРР Биоэнергетический потенциал в агропромышленном секторе Казахстана [Электронный ресурс] - https://www.ebrd.com/home.

32 Бюро национальной нтатистики Агентства по стратегическому планированию и реформам Республики Казахстан [Электронный ресурс] – https://stat.gov.kz/ru/industries/business-statistics/stat-forrest-village-hunt-fish/publications/5099.

33 Статистика лесного, сельского, охотничьего и рыбного хозяйства [Электронный ресурс] - https://stat.gov.kz/official/industry/14/statistic/7.

34 Статистика окружающей среды. Об охране атмосферного воздуха в Республике Казахстан (2022г.) [Электронный ресурс] - https://stat.gov.kz/ru/industries/environment/stat-eco/publications/68178/.

35 Статистика окружающей среды, выбросы твердых загрязняющих веществ [Электронный ресурс] - https://stat.gov.kz/ru/industries/environment/stat-eco/.

36 Недостаточный уровень переработки отходов - одна из наиболее весомых экологических проблем Казахстана [Электронный ресурс] - https://www.kt.kz/rus/reviews/nedostatochnyy_uroven_pererabotki_othodov_-_odna_iz_1377946253.html

37 Статистика промышленного производства [Электронный ресурс] - https://stat.gov.kz/ru/industries/.

38 Айтуганова С.Г., Кусаинова Б.М. Исследование основных свойств топливных брикетов из коксовой мелочи // Наука в центральной России. – 2016. – №2 (20). – С.71-76.

39 Характеристики лузги подсолнечника [Электронный ресурс] - https://phyllis.nl/Browse/Standard/ECN-Phyllis.

40 Характеристики лузги подсолнечника [Электронный ресурс] - https://www.feedtables.com/content/sunflower-hulls.

41 Характеристики лузги гречихи [Электронный ресурс] - https://link.springer.com/article/10.1007/s13399-022-03552-4/tables/3.

42 В. Н. Чмель. Использование биомассы в качестве альтернативного топлива // Институт технической теплофизики. – 2012. – № 131. – С. 65-69.

43 J. Burum. Characterization of F acterization of Fall Lea all Leaves as a Sour es as a Source of Cellulosic Ethanol ce of Cellulosic Ethanol // Journal of Undergraduate Research at Minnesota State University. – Mankato, 2008. – Vol. 8.

44 Характеристики листьев [Электронный ресурс] - https://phyllis.nl/Browse/Standard/ECN-Phyllis#leave.

45 Шурхно Р. А., Ахмадуллина Ф. Ю., Сироткин А. С.. Активность целлюлоз в растительных кормах и вторичном сырье в процессах их заготовки, переработки и хранения // Вестник технологического университета. – 2015. – Т.18. –№7.

46 Характеристики жмыха подсолнечника [Электронный ресурс] - https://phyllis.nl/Browse/Standard/ECN-Phyllis.

47 SNI 01-6235-2000. Национальный Индонезийский стандарт био-угольных брикетов. – Индонезия, 2000.

48 ГОСТ Р 54186-2010 EN 14774-1:2009. Биотопливо твёрдое. Определение содержания влаги высушиванием. – М., 2010.

49 ГОСТ Р 54185-2010 EN 14775:2009. Биотопливо твёрдое. Определение зольности. – М., 2010.

50 ГОСТ 32990-2014 EN 15148:2009. Биотопливо твёрдое. Определение выхода летучих веществ. – М., 2015.

51 ГОСТ 32987-2014 EN 15103:2009. Биотопливо твёрдое. Определение насыпной плотности. – М., 2015.

52 ГОСТ 21289-2018 Брикеты угольные. Методы определения механической прочности. – М., 2020.

53 ГОСТ 33103.1-2017 ISO 17225-1:2014. Биотопливо твёрдое. Технические характеристики и классы топлива. – М., 2017.

54 Спирин Н. А. Методы планирования и обработки результатов инженерного эксперимента: учебное пособие / Н. А. Спирин [и др.]; под ред. Н. А. Спирина. – УПИ : – Екатеринбург, 2003. – 260 с.

55 Штерензон В. А. Моделирование технологических процессов: конспект лекций. – Екатеринбург : Изд-во Рос. гос. проф.-пед. ун-та, 2010. – 66 с.

56 Рогов В. А. Методика и практика технических экспериментов: учебное пособие. – М. : Академия, 2005. – 288 с.

57 Хартман К. Планирование эксперимента в исследовании технологических процессов. – М. : Мир, 1977. – 552 с.

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