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USE OF PYROCARBON AND BIOMASS IN THE DEVELOPMENT OF COMBINED FUEL BRIQUETTES

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Abstract. An analysis was performed on the potential integrated use of alternative energy sources for producing fuel briquettes. This includes pyrocarbon generated through low-temperature pyrolysis of industrial and household plastic waste, as well as waste from the woodworking, pulp and paper, and agricultural industries. The process of forming fuel briquettes by cold pressing a mixture consisting of 60–70 wt.% pyrocarbon and 30–40 wt.% biomass (sawdust, corrugated cardboard, buckwheat, sunflower, wheat) was investigated. The effect of corn starch on the mechanical strength of the fuel briquettes was determined, which is attributed to the formation of inter- and macromolecular hydrogen bonds between the biomass and pyrocarbon components. It was found that the heat of combustion of the developed fuel briquettes is within the range of 4800–5100 Kcal/kg. Based on the results obtained, the effective use of these fuel briquettes in autonomous heating boilers for industrial, administrative, and residential buildings is proposed.

Keywords: fuel briquettes, heat of combustion, alternative energy sources.

1. Introduction

Uncontrolled accumulation of solid industrial and domestic waste, the lack of effective technologies for their utilization and processing is a major environmental problem that requires urgent resolution. The implementation of the Sustainable Development policy allows the EU countries to solve a number of such problems in the context of the concept of the "necessary criterion": economic growth, social development and environmental protection (Spangenberg, 2017). The Sustainable Development goals of Ukraine specified in the work (Decree of the President of Ukraine On the Sustainable Development Goals of Ukraine for the period up to 2030 dated September 30, 2019 No. 722/2019) are very close and meet the requirements of the EU countries. An important part of this concept in solving environmental issues is safe constant and integrated strategy for waste management, starting from the moment of their formation to the final products of processing.

Today, the transition from fossil fuels (oil, gas, coal) to renewable energy, which accumulates solar energy (PV-modules), wind (wind power) and hydrogen (hydrogen energy, fuel cells), is increasingly seen as a global fundamental problem for the entire global energy system (Qusay et al., 2025). The latest scientific developments of the world's leading countries in the energy sector focus, first of all, on the transition of their own fuel and energy sector to "green" energy. At the same time, it is undeniable that each country chooses its own segment of "green" energy development, based on its economic, industrial, scientific resources, as well as the effective use of natural potential and alternative

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energy sources (Korokhodova et al., 2022; Pstrowska et al., 2024; Miroshnichenko et al., 2022). In addition, it should be noted that the combustion of fossil fuels (81 % of primary energy supply) is a major factor in the growth of fuel gas emissions, which lead to global climate change and the deterioration of the planet's ecology. In this context, the effective use of renewable energy sources can solve not only a number of energy supply problems, but also contribute to the reduction of gas emissions from fossil fuel combustion, which will significantly improve the ecology of the environment (Khudolieieva et al., 2016; Yalechko, 2021). Among alternative energy sources, the use of biomass of various origins (wastes from the woodworking, pulp and paper, and agricultural industries) in the production of solid fuel occupies a prominent place, as it has a high calorific value/calorific value, is neutral in terms of carbon dioxide emissions, and has great energy potential (Heletukha et al., 2018; Korinchuk, 2021). According to Ukraine's Law No. 1391-XIV, dated January 14, 2020, "On Alternative Fuels", alternative types of solid fuels include both household and industrial waste. Household waste consists of materials such as paper, wood, and corrugated cardboard, while industrial waste includes plastics and textiles. At present, these materials are not widely recycled and are often incinerated to generate thermal or electrical energy (Ranskyi et al., 2023; Storoshchuk et al., 2021; Topal et al., 2021). However, these alternative fuels can be effectively processed into fuel briquettes, which demonstrate improved calorific value. fuel briquettes with improved calorific value. According to data from Roadmap for the Development of Bioenergy in Ukraine until 2050 and Action Plan until 2025 (2021), the energy potential of biomass in Ukraine exceeds 23 million tons of fuel equivalent per year. This includes: energy crops and wood waste: 6.7 million tons; straw from grain crops: 4.6 million tons; other crop waste: 5.2 million tons; liquid fuels (such as biodiesel and ethanol): 2.2 million tons; peat: 0.6 million tons; other types: 4.0 million tons. Therefore, the use of these alternative energy sources (wood, peat, other non-wood waste), primarily by local governments in the fuel and energy balance of regions, could significantly improve the level of their energy supply (Kindzera et al., 2025).

Thus, taking into account the available large amount of energy biomass (wastes from woodworking, pulp and paper, agricultural industries) and potential pyrocarbon, as a product of pyrolysis of a huge amount of polymer waste (polyolefins), their use is important and promising in the development, production and use of combined fuel briquettes (Korinchuk, 2021). However, a number of unexplored issues arise in the development of optimal formulations of combined fuel briquettes, the study of their calorific value, mechanical strength and general environmental issues of their possible use. These issues became the subject of research in this work.

The purpose of the work is to analyze the physicochemical characteristics of the starting raw materials (biomass waste, pyrocarbon), develop a method for obtaining combined fuel briquettes based on them and evaluate their calorific value, mechanical strength for dumping and ash content.

2. Experimental part

2.1. Materials and Methods

Table 1 shows the most important physicochemical characteristics of fuel briquettes and their individual components, which indicate the prospects for their use as alternative energy sources.

The data given in Table 1 were used by us in determining the components of the studied combined fuel briquettes. In this case, it is necessary to note the following features:

– brown coal and pyrocarbon obtained during the pyrolysis of polymer waste ((Korinenko; Ranskiy, 2023); item 1. Table 1) have a maximum calorific value of 4300–6500 Kcal/kg and act as the main component of composite fuel briquettes;

– waste from the woodworking and pulp and paper industries (item 2, Table 1) have a significantly lower calorific value of 2860–4500 Kcal/kg, however, the presence of natural (lignin, resin) or additionally introduced (polyvinyl acetate, starch) substances in their composition allows obtaining fuel briquettes with satisfactory mechanical properties;

– non-wood agricultural waste (item 3, Table 1) has a calorific value similar to wood waste of 3340–4800 Kcal/kg, however, it is ~1.5 times higher than wood waste, which makes it the main alternative source of renewable energy, based on the total volume of biomass in Ukraine.

The main energy component of fuel briquettes was pyrocarbon obtained as a product of low-temperature pyrolysis of industrial and household polymer waste (polyolefins) according to the methods (Korinenko; Ranskiy, 2023).

Table 1

Composition and main technical characteristics of fuel briquettes

Components of fuel briquettes		**Humidity, wt. %**	**Calorific value, Q_3**		**Ash content, wt. %**	**Literature**
			MJ/kg	**Kcal/kg**		
1. Lignite, pyrocarbon from plastic recycling						
Lignite	standard*	25–30	17.99	4300	25	(Smyrnov et al., 2011)
	briquette	3–4	23.01	5500	10–25	(Smyrnov et al., 2011)
Pyrocarbon	standard*	2.4	27.7	6500	19.5	(Makarov et al, 2024)
	briquette	10–14.5	25.6–26.0	6120	12.3	(MusOboz, Smith's Look, No. 266, 2025)
2. Waste from the woodworking and pulp and paper industries						
Wood	standard*	30–40	17.15	4100	0.2–1.7	(Skliarenko, 2017)
	briquette	5–7	18.83	4500	1.0	(Skliarenko, 2017; Burova et al., 2016)
Wood sawdust	standard*	30–40	8.1–12.4	2860	0.2–1.7	(Skliarenko, 2017)
	briquette	<10	17.0	4060	1.5	(Skliarenko, 2017; Burova et al., 2016)
Cardboard	standard*	6.1–6.5	18.56	4436	6.5	(Burova et al., 2016; Burova& Vorobiov, 2016)
	briquette	7.6	16.0–18.0	3820	3.0–3.5	(Burova et al., 2016; Burova & Vorobiov, 2016)
3. Non-wood waste from the agricultural industry						
Buckwheat straw	standard*	7.47	17.04	4070	1.5	(Klymenko et al., 2017)
	briquette	5.10	20.08	4800	1.5–6.0	(Klymenko et al., 2017)
Sunflower stem	standard*	10–20	14.65	3500	3–7	(Skliarenko, 2017)
	briquette	<10	18.00	4300	4.3	(Skliarenko, 2017)
Sunflower husk	standard*	15	15.43	3690	3–7	(Skliarenko, 2017)
	briquette	8.3	17.2–18.3	4110	4.0	(Burova et al., 2016; Ranskyi et al., 2023)
Wheat straw	standard*	10–20	14.00	3340	4–5	(Skliarenko, 2017)
	briquette	7.0	16.15–17.15	3860	80	(Burova et al., 2016)

Note: standard * – individual substance.

As fillers for the studied fuel briquettes, waste from the woodworking, pulp and paper, and agricultural industries was used:

– sawdust of deciduous trees, pre-crushed to a particle size of 2.5 mm and with a moisture content of 5–20 wt.%;

– corrugated cardboard made from MS-2B-2 waste paper, with corn starch as the adhesive base, produced by PJSC Kyiv Paper and Cardboard Plant (Obukhov);

– non-wood plant raw materials (wheat, sunflower, buckwheat), pre-dried and crushed to a particle size of 3–5 mm, obtained from the agricultural enterprise LLC Agro-Etalon in Vinnytsia region. The chemical composition of the used non-wood plant raw materials, given in Table 2, indicates their lignin-cellulose structure and the possibility of forming fuel briquettes during their pressing.

The following physical and chemical characteristics were determined for the obtained pyrocarbon: moisture, ash content and the ratio of organic and inorganic particles.

Moisture content was determined on the AXIS ADGS 50 moisture analyzer scales. Drying of the pyrocarbon sample was carried out in an air atmosphere at 105 °C until a constant sample mass was established. The obtained pyrocarbon moisture content was 16.43 ± 2.50 % by weight.

The ratio of organic and inorganic components in a dry pyrocarbon sample was determined by its combustion/ashing in a muffle furnace at a temperature of 550 °C until the carbon was completely burned out. The ratio of inorganic fraction: organic fraction was 46.73 : 53.27 % by weight.

During the study, 10 samples of combined fuel briquettes were produced with different percentages of the main components (Table 4). Their calorific value was determined using the calorimetric method in accordance with DSTU ISO 1928:2006 (ISO 1928:1995, IDT). Portions of each sample were carefully crushed and dried for three days to achieve an air-dry state. The calorific value was measured by combusting the samples in an oxygen atmosphere at a pressure of 2.5–3.0 MPa using a bomb calorimeter (IKA S200, Germany). The reported values represent the average of two independent measurements and are presented in Table 4.

Table 2

Chemical composition of non-wood plant raw materials, wt. %

Plant raw materials		Cellulose	Hemicellulose	Lignin	Ash content	Literature
Wheat	stalks	44.3	26.7	16.5	6.6	(Hanzhenko& Humentyk, 2016; Machado et al., 2016)
Sunflower	stalks	40.6	21.3	20.1	3.0	(Hanzhenko & Humentyk, 2016; Machado et al., 2016)
	husks	41.0	24.0	27.8	0.4	(Hanzhenko & Humentyk, 2016; Machado et al., 2016)
Buckwheat	stalks	39.9	28.2	20.0	2.8	(Silva & Chandel, 2012)
	husks	36.0	32.0	19.5	0.3	(Hanzhenko; Humentyk, 2016; Machado et al., 2016)
Wood*	sawdust	40–45	20–30	19–30	0.3–0.8	(Hanzhenko & Humentyk, 2016; Machado et al., 2016)

Note: * – data are provided for comparison with the corresponding characteristics of non-wood raw materials.

Table 3

Mass content of oxides in the ash of a pyrocarbon sample

Element	Formula	Amount, wt.%
Aluminum oxide	Al_2O_3	5.218
Calcium oxide	CaO	26.786
Iron oxide	Fe_2O_3	9.852
Potassium oxide	K_2O	20.867
Manganese oxide	MnO_2	-
Lead oxide	Pb_2O_3	2.753
Sulfur oxide	SO_2	0.705
Silicon oxide	SiO_2	16.050
Titanium oxide	TiO_2	8.541
Zinc oxide	ZnO	0.228

Table 4

Composition and calorific values of the studied fuel briquettes

Example number	Components of fuel compositions, %								Q_3, Kcal/kg
	P	CC	WS	BS	BH	SS	SH	WSt	
1	70	15	15	–	–	–	–	–	4968.1
2	60	20	–	20	–	–	–	–	4800.0
3	60	20	–	–	20	–	–	–	4928.4
4	60	20	–	–	–	20	–	–	4828.3
5	60	20	–	–	–	–	20	–	4909.1
6	60	20	–	–	–	–	–	20	4800.2
7	60	20	–	–	10	–	10	–	4895.0
8	60	20	5	–	5	–	5	5	4631.8
9	70	15	–	–	15	–	–	–	5127.4
10	70	15	–	–	–	–	15	–	5077.4

Symbols: P – pyrocarbon; CC – corrugated cardboard of the MS-2B-2 brand; WS – wood sawdust; BS – buckwheat straw; BH – buckwheat husk; SS – sunflower stalks; SH – sunflower husk; WSt – wheat straw.

The mechanical strength of combined fuel briquettes for dropping was carried out according to standard method (GOST 21289-2018). The briquette sample was dropped from a height of 0.5 m onto a metal plate and the amount of fines formed was calculated by sieving it through a sieve with 25 mm openings. The amount of such particles was 4.5–15.0 % by weight, which meets the requirements of GOST 21289-2018 and coincides with the results of a number of other works.

Table 5

Wave numbers (ν, δ, cm⁻¹) of absorption maxima in the IR spectra of cellulose, lignin, and pyrocarbon

Components of fuel briquettes	Functional group, cm^{-1}							
	ν(OH), δ(OH)	ν(CH), ($-CH_2$)	ν(C=O), (C(=O)O)	ν(C(=O)H)	ν($C=C_{Ar}$)	δ(C-H)	ν($CO-CH_3$)	ν(C_{Ar}-H)
Cellulose	3.400 3.408	2.901	1.740	1.630	–	1.372 1.375	1.060 9.00	–
Lignin	3.000- 3.700	2.900	1,747 1,720	1.663	1.515 1.512 1.508	1.370	1.275 1.225	860
Pyrocarbon	3.304 3.117	–	1,545	–	1.124 1.036	–	–	–

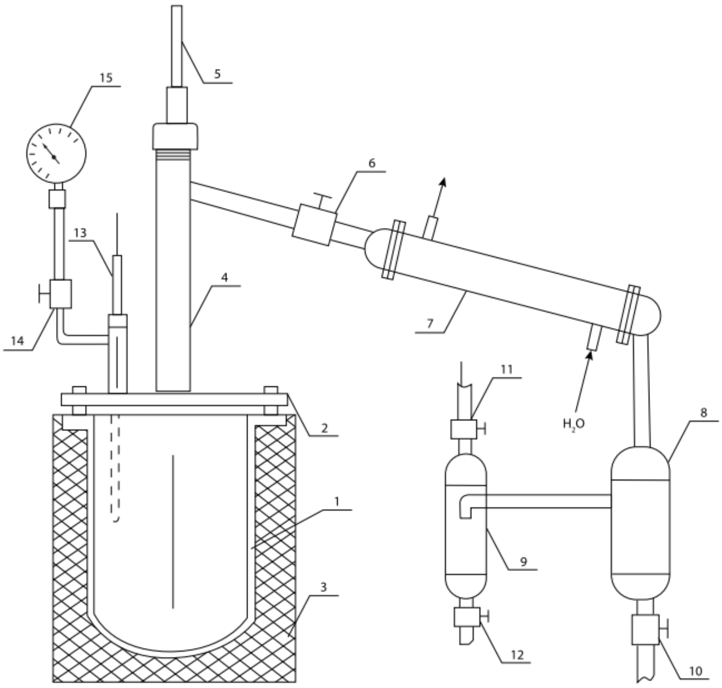

Fig. 1. Installation for low-temperature pyrolysis of polyolefins:
1 – reactor; 2 – lid; 3 – electric heater with insulating housing;
4 – separation column; 5, 13 – thermocouples; 6, 10, 11, 12,
14 – shutoff valves; 7 – condenser; 8 – heavy fraction collector-condenser;
9 – light fraction collector-condenser; 15 – manometer

IR spectral studies of the obtained pyrocarbon were carried out using an IR-Fourier spectrometer SRAFFINITY-1S Shimadzu (Japan) in the range of 4000–400 cm^{-1}. Identification of functional groups on the pyrocarbon surface was performed using LabSolutions IR software and according to other original works (Balalaiev, 2012). The obtained data are presented in Table 5.

2.2. Experimental procedure

2.2.1. Obtaining pyrocarbon

Pyrocarbon, which was studied as part of solid fuel briquettes, was obtained by low-temperature pyrolysis of polyolefins (polyethylene, polypropylene, polystyrene) in a batch plant shown in Fig. 1. Process conditions: inert medium: t = 290–410 °C; excess pressure P = 1.1–1.2 atm; τ = 3.5 hours. Yield of pyrolysis products: pyrolysis liquid – 85.6 %, pyrolysis gas – 5.6 %, pyrocarbon – 3.8 % by weight. (Korinenko; Ranskiy, 2023).

Pyrocarbon formed during the low-temperature pyrolysis of polymer waste is an energy-dense and environmentally friendly solid fuel, as it does not contain heavy metals, halogens, nitro- or sulfur-containing organic compounds, and does not require additional purification (Table 3).

2.2.2. Obtaining fuel briquettes

The main method (example No. 2, Table 3) was used to prepare a composite fuel briquette. Crushed corrugated cardboard (20%), previously soaked in water, was fed into a mixer and thoroughly combined with buckwheat straw (3–6 mm particle size, 20 %) and pyrocarbon (60 %). The resulting mixture was transferred to an accumulator, from which it was fed to a hydraulic press (MS-500) for briquetting. After pressing, the fuel briquettes were dried to a constant weight and then packed.

Other fuel briquettes (No. 1, 3–10), the compositions of which are given in Table 4, were produced using a similar procedure.

3. Results and Discussion

The performed studies involved producing fuel briquettes by pressing a pre-prepared charge without heating, with the optional addition of binding components. Due to the high heat capacity of pyrocarbon, the resulting fuel briquettes exhibited a high calorific value in the range of 4800–5127 Kcal/kg (Table 4), while the wood and non-wood fillers contributed primarily to their excellent mechanical and environmental properties. These properties were determined by the composition and physicochemical characteristics of the raw materials, as presented in Table 2. The studied polymeric, wood, and non-wood natural raw materials consist mainly of lignocellulose and feature of the presence on its surface functional groups such as hydroxyl, alkoxyl, carboxyl, and acetyl (cellulose, hemicellulose, and lignin) (Long et al., 2023; Nanda et al., 2013; Volynets et al., 2017; Castillo et al., 2016; Vârban et al., 2021; Voronych, 2012; Huang et al., 2012; Halysh et al., 2016), alpha-glycosidic bonds from corn starch (Movchaniuk; Ostapenko, 2024), and inter- and macromolecular hydrogen bonds in cellulose, hemicellulose, and lignin fibers (Kshyvetskyi et al., 2024). Table 5 presents the characteristic IR spectral oscillations of functional groups in cellulose (Nanda et al., 2013; Castillo et al., 2016; Voronych et al., 2012), lignin (Castillo et al., 2016; Huang et al., 2012), and pyrocarbon (Balalaiev, 2012), obtained during the pyrolysis of polymer waste. The reported absorption maxima of functional groups in the chemical composition of the fuel components are determined not only by their individual properties as lignocellulosic polymers, but also by their ability to form inter- and macromolecular hydrogen bonds. It is evident that the maximum number of hydrogen bonds in the following systems: a) cellulose/hemicellulose/ lignin–starch (amynopectin); b) cellulose–pyrocarbon–cellulose; c) cellulose–starch–pyrocarbon (Fig. 2) will determine the highest mechanical strength of fuel briquettes based on pyrocarbon, wood, and non-wood renewable raw materials.

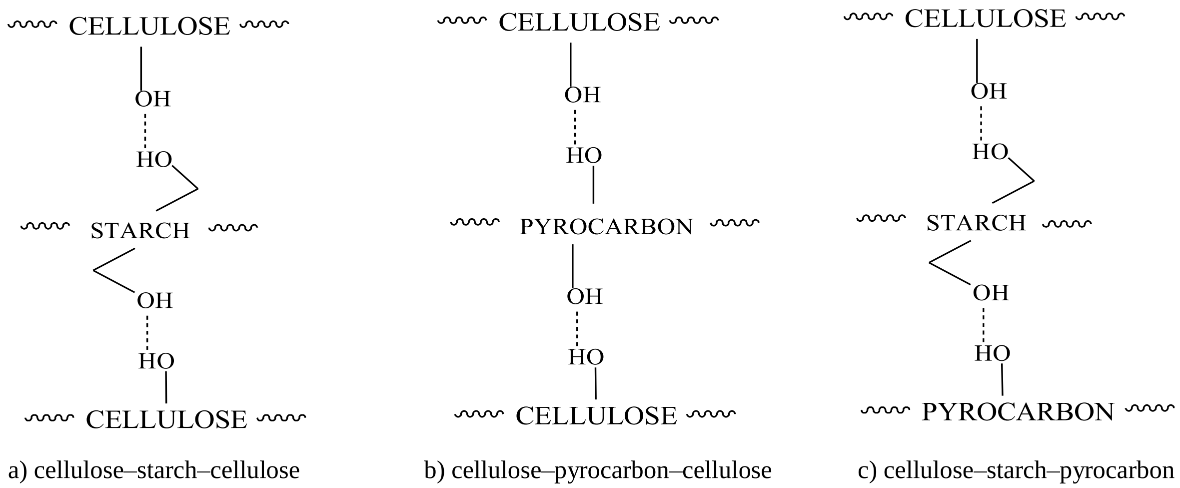

Fig. 2. Formation of possible hydrogen bonds between the components of the studied fuel briquettes

Similar conclusions regarding the formation of a structured interface between coal and organic binders/adhesives, which provides high mechanical (cohesive) properties of solid fuel during briquetting, were reported in previous studies (Movchaniuk; Ostapenko, 2024).

Thus, the inclusion of waste from the wood (sawdust), pulp and paper (corrugated cardboard), and agricultural industries in the composition of the studied fuel briquettes at 30–40 wt.% (Table 4) ensures both their environmental friendliness and the required mechanical strength.

Comparison of the calorific value of the obtained pyrocarbon with that of brown coal commonly used in briquetting shows that pyrocarbon releases 1.5 times more heat upon combustion (Table 1; Smyrnov et al., 2011; Burova; Vorobiov, 2016). In the case of the fuel briquettes, this difference is only 1.1 times. Comparing the calorific value of pyrocarbon with other components of the studied briquettes (items 2 and 3, Table 1) shows that they release approximately 1.6–2.3 times less heat when burned. However, the additives (industrial and agricultural waste; items 1–10, Table 4) provide high mechanical strength and environmental safety to the final product. Their inclusion increases the oxygen and hydrogen content of the fuel briquettes, thereby reducing CO_2 emissions during combustion and decreasing the final ash content by 1.6–2.5 times, with the exception of wood, buckwheat, and wheat straw (Table 1). At the same time, the heat of combustion of the produced fuel briquettes was generally 1.1–1.4 times higher than that of the individual fuel components (Table 1).

Table 6

Comparison of the specific energy cost of fossil fuels, biofuels and biomass fuel briquettes

Type of energy carrier or fuel	**Price (01.01.2025)**	**Lower calorific value, MJ/kg**	**Cost of a unit of energy in fuel/energy carrier, UAH/GJ**
	A	B	A / B
1. Fossil fuels, electricity			
Natural gas for the population	7960 UAH/thousand m^3	34.0	234
Natural gas for industry	27000 UAH/thousand m^3	34.0	794
Fuel oil, M100	12420 UAH/ton *	42.0	296
Coal	7000–16000 UAH/ton *	25.0	280–640
Electricity	4,32 UAH/kWh	–	1201
2. Fuel from natural raw materials			
Firewood (humidity 40%)	1500 UAH/ton *	10.0	150
Straw in bales	2000 UAH/ton *	14.0	143
3. Biomass fuel briquettes			
RUF fuel briquettes	5900 UAH/ton *	18.0	327
Fuel briquettes made from cereal straw	5000 UAH/ton *	17.0	294
Fuel briquettes from sunflower husks	5000 UAH/ton *	18.0	277
NESTRO fuel briquettes	3250 UAH/ton *	19.0	171

Note: * – indicative price; the real price is influenced by factors such as region, manufacturer, quality indicators of a particular batch of product.

Prospects and advantages of using combined fuel briquettes. During the war between Ukraine and the russian federation, energy generation and consumption (nuclear power stations, thermal power stations, hydroelectric power stations) fell significantly, and this deficit can be partially compensated by the effective use of alternative energy sources (Table 1) in the production of fuel briquettes. After all, the production of fuel briquettes and pellets from biomass in Ukraine is not new. For example, the growth of the bioenergy sector during 2010–2016 was estimated at an average of 45 % per year in the production of biofuels and 35 % per year in the total supply of primary energy from them. Today, in the production of fuel briquettes, the largest share of the raw materials used is wood, husk, straw and reed. The volume of the Ukrainian market of fuel briquettes for individual use by the population is estimated at approximately 1 million tons/year with its growth to 3 million tons/year by 2035 (, 2018). In addition, it is necessary to note the high calorific value (Table 4) and satisfactory mechanical and environmental properties of the developed combined fuel briquettes. Their biocomponents are neutral in terms of carbon monoxide emissions, and the pyrocarbon used had a low ash content (Table 3). The economic prospects of fuel briquette production are given in Table 6. Fuel briquettes have a lower specific cost (UAH/GJ) compared to the specific cost of energy of natural raw materials and are almost identical to fossil fuels, with the exception of electricity.

The performed research on the development of new fuel briquettes based on pyrocarbon, wood, and non-wood renewable raw materials allows us to make the following generalizations:

– obtaining fuel briquettes corresponds to the basic principles of the circular economy: waste from a number of industries (woodworking and pulp and paper industries) and technologies (pyrolysis processing of industrial and household plastic waste), agricultural waste becomes the starting raw material for obtaining the demanded final product – fuel briquettes with their subsequent effective use;

– enterprises of the woodworking and pulp and paper industries have accumulated a large amount of waste that can be effectively processed in the manufacture of solid fuel briquettes;

– the studied method of manufacturing solid fuel briquettes does not require additional introduction of binders of organic or inorganic nature, which significantly increases their efficiency, environmental friendliness, and heat of combustion;

– due to the presence of the required amount of corn starch (linear amylase, branched amylopectin), briquetting is carried out without additional heating of the fuel briquette mixture before pressing/pressing the initial charge;

– the advantage of the performed research is the simplicity and accessibility of technological equipment, the accessibility of raw materials, and the cost-effectiveness of using the resulting products for heating both industrial and domestic premises.

Thus, obtaining solid fuel briquettes allows you to save on the use of fossil energy sources (oil, gas, coal) by using alternative energy-intensive raw materials (wastes from the woodworking, pulp and paper, agricultural industries, and pyrocarbon from pyrolysis processing of plastic waste), as well as expand the scope of their effective application as alternative energy sources.

4. Conclusions

The possibility of the comprehensive use of pyrocarbon, obtained from the pyrolysis of industrial and household polymer waste, as well as waste from the woodworking, pulp and paper, and agricultural industries, for the production of new fuel briquettes has been demonstrated. The effect of corn starch on the mechanical properties of the resulting fuel briquettes was investigated. The calorific value of the developed fuel compositions was determined to be in the range of 4800–5100 Kcal/kg. The mechanical strength of combined fuel briquettes to dropping and their ash content were investigated. Potential areas for the effective use of these solid fuel briquettes have been proposed.

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