International Journal of Innovative Research and Scientific Studies, 8(4) 2025, pages: 2763-2776

IJIRSS
International Journal of Innovative Research & Scientific Studies

ISSN: 2617-6548

URL: www.ijirss.com

Sustainable production of metallurgical coke from technogenic wastes: A circular approach to waste utilization

Lyazat Tolymbekova[1], Almat Aubakirov[2], Yermagambet Abdrakhmanov[3], Eldar Kopishev[4], Fuad Khoshnaw[5*]

[1,4]Faculty of Natural Sciences, Department of Chemistry, L.N. Gumilyov Eurasian National University, Astana 010000, Kazakhstan.
[2,3]Department of Metallurgy, Faculty of Engineering, Toraighyrov University, Pavlodar140000, Kazakhstan.
[5]School of Engineering and Sustainable Development, De Montfort University, Leicester, United Kingdom.

Corresponding author: Fuad Khoshnaw (*Email: fuad.khoshnaw@dmu.ac.uk*)

Abstract

The present study is devoted to evaluating the possibility of using coal fines and waste from electrolysis production, spent anode material, as an alternative raw material for the production of metallurgical coke suitable for use in agglomeration processes. As part of the study, laboratory briquetting of raw materials, coking of the obtained briquettes, and a comprehensive study of the properties of the obtained coke were carried out. The purpose of the study was to assess the potential of processing man-made carbon-containing waste and to determine the optimal composition of the charge for coke production. A thermal analysis made it possible to establish optimal coking temperature conditions, the nature of the release of volatile components, and the features of the restructuring of the carbon matrix, which are of key importance for predicting the quality of the final product. The charge materials demonstrated high thermal stability and ensured the production of high-quality coke suitable for use in sintering processes. Measurements of electrical resistivity showed a value of 0.21 ohm· cm, indicating the high electrical conductivity of the material at low temperatures due to the peculiarities of the microstructure and phase composition of coke. Additionally, the calorific value of the briquettes was 6840.8 kcal/kg, indicating high fuel efficiency. The data obtained confirm the potential of replacing traditional high-quality coal with alternative briquetted raw materials that provide the necessary thermal energy and temperature conditions during coking. The results of the study demonstrate the possibility of effectively using spent anode material in a mixture with coal fines and coal pitch as a binding component for the production of coke suitable for use in metallurgical processes. The research supports the development of environmentally sustainable approaches to the disposal of carbon-containing industrial waste and opens prospects for their industrial use as resource-saving and environmentally oriented alternatives to traditional coke.

Keywords: Agglomeration, coal pitch, coal, coke, ferrous metallurgy, spent anode material, thermal analysis.

DOI: 10.53894/ijirss.v8i4.8554
Funding: This work is supported by the Committee of Science of the Ministry of Science and Higher Education of the Republic of Kazakhstan (Grant number: AP19679492).
History: Received: 4 June 2025 / **Revised:** 8 July 2025 / **Accepted:** 10 July 2025 / **Published:** 16 July 2025

Competing Interests: The authors declare that they have no competing interests.
Authors' Contributions: All authors contributed equally to the conception and design of the study. All authors have read and agreed to the published version of the manuscript.
Transparency: The authors confirm that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.
Publisher: Innovative Research Publishing

1. Introduction

The increasing demand for environmentally friendly production methods encourages researchers to explore alternative raw materials and recycling techniques in metallurgical processes. Ferrous metallurgy is currently experiencing rapid development due to the growing global demand for cast iron and steel across various industries. The modern strategy of large metallurgical enterprises focuses on producing high-quality steel while reducing costs, as well as paying particular attention to environmental protection and addressing key social and environmental issues. One of the most important technical directions in this field is the economically feasible disposal of solid waste from industrial enterprises [1].

Coke plays an important role in metallurgy, acting both as a fuel and as a reducing agent in the smelting of metal alloys. In particular, the sintering industry requires high-quality coke with sufficient thermal and structural properties. Traditionally, such coke is produced from high-quality coking coals, which are becoming increasingly expensive, limited in availability, and burdensome for the environment. Additionally, not all types of coking coals are compatible with each other; differences in brand or composition can reduce the strength and integrity of the final coke product, especially after coking. Therefore, one of the key tasks in coke production is to achieve an optimal balance between economic efficiency and coke quality [2].

In this context, using carbon-rich industrial waste has become a particularly relevant and promising area [3-6]. This approach makes it possible to partially or completely replace expensive traditional raw materials, which leads to lower production costs and increased environmental friendliness. The use of industrial waste also makes it possible to achieve several strategic goals simultaneously: minimize the environmental impact, reduce the amount of waste requiring disposal, and support the transition to resource-saving technologies [7, 8]. However, the success of this approach depends on a deep understanding of the thermochemical decomposition of waste, optimization of carbonation parameters, and detailed characterization of the final coke to ensure its suitability for industrial use in sintering processes.

The purpose of this study is to evaluate the potential of using coal fines and spent anode material from electrolysis production as alternative raw materials for the production of metallurgical coke. These industrial by-products are rich in carbon but remain underutilized, representing missed economic opportunities and potential environmental hazards. Although previous studies have explored various methods for producing coke from waste, there is a clear gap in the systematic analysis of the use and waste of spent anode material from electrolysis production as a carbon source.

Thus, the main research issue considered in this study is the possibility of obtaining metallurgical coke suitable for agglomeration from spent anode material mixed with coal fines and coal pitch as a binding component suitable for use in metallurgical processes.

To address this issue, the study was conducted at the following stages:

- Determine the characteristics of raw materials (coal fines, spent anode material, and coal pitch).
- Preparation and briquetting of mixtures in various proportions.
- Coking of briquettes
- Comprehensive study of the properties of the obtained coke
- Evaluation of coke quality and its suitability for sintering

This research contributes to the development of sustainable and cost-effective technologies for the production of metallurgical coke using industrial carbon-containing waste.

2. Literature Review

The need to obtain cheaper fuel is currently one of the most urgent challenges in production. Therefore, finding new ways to utilize more affordable raw materials thereby reducing energy costs in sintering processes has become a priority [9, 10]. Researchers explored expanding the raw material base of metallurgy by incorporating unused natural fuel raw materials, such as peat, coal, and vegetable raw materials, as well as man-made resources from tailings dumps with pulverized fractions in briquetting processes. This approach opens new possibilities for the production of composite materials with predetermined properties and offers new prospects for the development of techno-ecology and materials science [11, 12].

Authors Chernyshova et al. [13] investigated briquetting of carbon-containing steelmaking waste to produce metallurgical coke. Coal tar sludge from the sedimentation tank of the by-products of the coke plant was used separately as a binder or in combination with other waste such as steel mill oil and coke oven pipeline deposits. An alternative filler with a low cost, coal obtained after cleaning the coal charge, was used. Coal briquettes of different compositions were tested in a semi-dense furnace with a movable wall when they were added to the coke mixture in an amount of 10 wt. %. The results showed that the coke quality parameters did not show significant deterioration as a result of the addition of coal briquettes.

Every year, the coking industry produces a significant amount of tarry and other wastes in byproduct plants. For the most part, these wastes have not been put to any practical use. In addition, an integrated factory produces several waste oils that differ in composition and quantity, e.g., wastes from the steel rolling-mill process. Researchers [14] investigated the possibility of using such waste materials as binders in a partial briquetting process for metallurgical coke production. Using this coking procedure, a strong metallurgical coke, not inferior in quality to coke from conventional coal blends, is produced at pilot and semi-industrial scales. The use of such wastes, some of which are classified as hazardous materials, will avoid the need for dumping, thereby contributing to environmental protection as well as reducing waste disposal costs.

The authors of Pavlovich et al. [15] investigate the use of waste in coke production. The utilization of solid domestic waste, plastic, rubber, leather, textiles, wood, and paper, in coking batches after mixing with residues from coal-tar stores at coke plants is investigated. All the solid domestic waste, considered especially plastic waste, increases the yield of coke in the >80 and >60 mm classes and the yield of tar and benzene. The introduction of plastics and a mixture of solid domestic waste with up to 1% of tar-storage residues does not impair the quality of the coke produced.

Other researchers [16] focused on the manufacture of briquettes by using carbon-containing wastes from steel making as fillers and binders for use in coke ovens to produce metallurgical coke. Coal-tar sludges from the tar decanter of a by-products coking plant were employed individually as a binder or combined with other wastes, such as oils from the steel rolling mills and deposits from the coke oven gas pipelines. Another objective of this study was to use alternative low-cost fillers, such as the coal-generated ash after routine cleaning operations in the coal stockyards, to reduce the overall cost of briquette manufacture. Partial briquetting of the charge enabled coke to be produced according to the specific requirements of the blast furnace.

Authors Rasskazova [17] investigated the rational physical and technological parameters of briquetting of brown coal raw materials are scientifically substantiated and established, ensuring an increase in the efficiency of its use. The idea of the work was that the establishment of rational parameters and a directional change in the strength characteristics of coal briquettes, with the introduction of a mechanically activated filler, ensures effective briquetting of low-grade brown coals.

While numerous studies have investigated the production of metallurgical coke from industrial waste, such as coal sludge and carbon-containing residues, significant challenges remain. Key areas requiring further research include the optimization of thermochemical processes, the improvement of coke properties, and the development of efficient waste treatment methods. Addressing these issues will be crucial for lowering production costs and mitigating environmental impacts. This study presents a novel method for producing metallurgical coke for sintering, using briquetted coal fines from the Ekibastuz deposit enriched with high-carbon spent anode waste from electrolysis production. This approach not only enhances the calorific value of the briquettes but also supports sustainable waste utilization by integrating two industrial by-products into a single high-value output.

3. Materials and Experimental Methods

3.1. Materials.

The following raw materials were used to prepare briquetted charges for metallurgical coke production:

- Coal fines from the Ekibastuz coal deposit (fraction size 0.3–3 mm), a by-product of coal mining operations, were selected as the primary carbon source due to their availability and low cost.
- Spent anode material, a carbon-rich residue (96–98% carbon) from the electrolysis process in aluminium production, was used as a carbon concentrator.
- Coal pitch was used as a binder because of its favorable coke-forming ability and low viscosity in the molten state, which ensured uniform binding of the components during briquetting.

3.2. Methodology.

The study involved selecting and preparing materials—coal fines from the Ekibastuz coal deposit, spent anode material obtained through electrolysis of aluminum, and coal pitch used as a binder. These raw materials were crushed, mixed in specific proportions, and molded into cylindrical briquettes using a laboratory stamping press under controlled pressure and temperature.

The formed briquettes were subjected to coking in a laboratory muffle furnace at a temperature of 1000°C to simulate the conditions of industrial coking. After coking, coke samples were evaluated for their thermal stability, electrical resistivity, and calorific value by analyzing the elemental composition of the coal. The thermal behavior and decomposition characteristics were studied using thermogravimetric and differential thermal analysis. The electrical conductivity of coke was assessed using a specialized laboratory setup.

This approach differs from previous studies in that it is the first time these materials have been investigated for the production of coke for agglomeration and focuses on combinations of industrial waste. The combination of industrial by-products used in this study and the optimization of the process, taking into account agglomeration requirements, distinguish it from earlier approaches.

The coke obtained under laboratory conditions is as close as possible in size to agglomeration cokes, meaning minimal energy will be spent on crushing. The advantage of fine fraction fuel is that its combustion occurs at a significantly higher rate compared to coarse-grained fuel, which allows for an increased vertical sintering rate of the ore [18, 19]. Thus, the operation before crushing will be practically excluded from the process, which reduces the energy consumption of the process.

In the course of preliminary studies and analysis of Ekibastuz coal, it was found that about 17% of the main volume of coal produced consists of coal fines with a particle size of approximately 0.3–3 mm. This allows for the production of fuel and coked briquettes with minimal preparation costs. The spent anode material is the residue of the burnt anode from an aluminium electrolyzer at the end of its operational cycle, which requires specialized methods for processing and disposal [20]. The most important raw material component in the production of most types of carbon products is binders, the quality of which largely determines the level of the physical and mechanical properties of the product. The favorable combination of high coke-forming ability and low viscosity in the molten state distinguishes coal tar from other types of binding materials for various carbon-containing compositions [21].

One of the widely known methods of coal research is thermal analysis. Among its various variants, the most informative are analytical techniques, which include a graphical representation of the dependencies of changes in the mass and temperature of the test sample on the heating temperature. They reflect changes in the composition and structure of the object under study when it is heated, and also indicate the destruction and/or formation of molecular bonds in it at each stage of thermolysis. The principle of constructing such dependencies is the basis of the derivatographic method. It allows you to monitor the change in the mass of the sample and the rate of its change during the experiment, and simultaneously record the release and absorption of heat, more precisely, an increase or decrease in the temperature of the object of study with a linear increase/decrease in temperature in the zone of thermal reaction [22-24]. Thus, it opens up the possibility of a consistent, detailed consideration of the various stages of heat treatment of coal from its drying to complete decomposition or burnout [25].

To evaluate the thermal behavior of the raw materials and to determine suitable processing conditions for coke production, a series of thermogravimetric and differential thermal analyses were performed. These analyses provide insights into mass loss behavior, thermal stability, and decomposition patterns under controlled heating.

The sample weight was 62.5 mg, and α-aluminum oxide calcined at 1200°C was used as a reference sample (standard). The heat treatment of the coals was carried out in an atmospheric environment.

The thermal decomposition curves of the studied samples were obtained using a Synchronous Thermal Analyzer Derivatograph. Refer to Figure 1. The experiments were conducted while heating the sample to 900°C at a rate of 10°C/min.

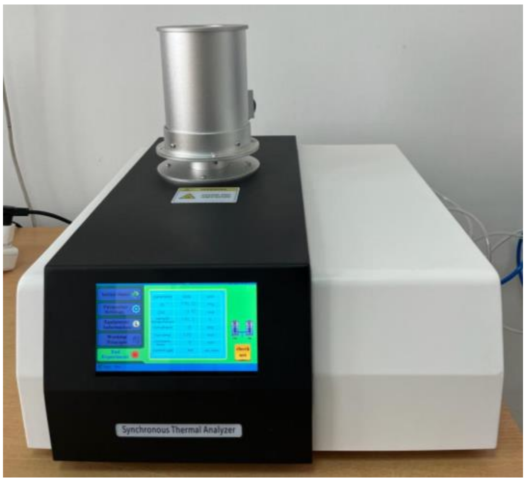

Figure 1.
Synchronous Thermal Analyzer Derivatograph.

3.2.1. Experimental Methods

Laboratory tests were conducted at the University of Toraighyrov to obtain coke. Based on our previous research, the most optimal composition of the charge was selected, which included the following components: coal fines – 50%, spent anode material – 30%, and coal pitch – 20%.

The charge with a fraction of 0-3 mm was weighed on an electronic balance from Techprom and mixed in a laboratory mixer LS-AB-10 with heating to 150 °C, while the coal pitch softened and bound the charge into a homogeneous mass. The pitch is characterized by a sufficiently high coke number and sinterability, due to which the resulting coke binds the carbon-graphite product into a single monolith, and at the same time, is mobile enough for the molded mass to have the necessary plasticity. After that, the resulting combustible mixture was loaded into the sleeve of a laboratory stamping press for briquetting (see Figure 2), where it was molded into a briquette under a specific pressure of 25 MPa.

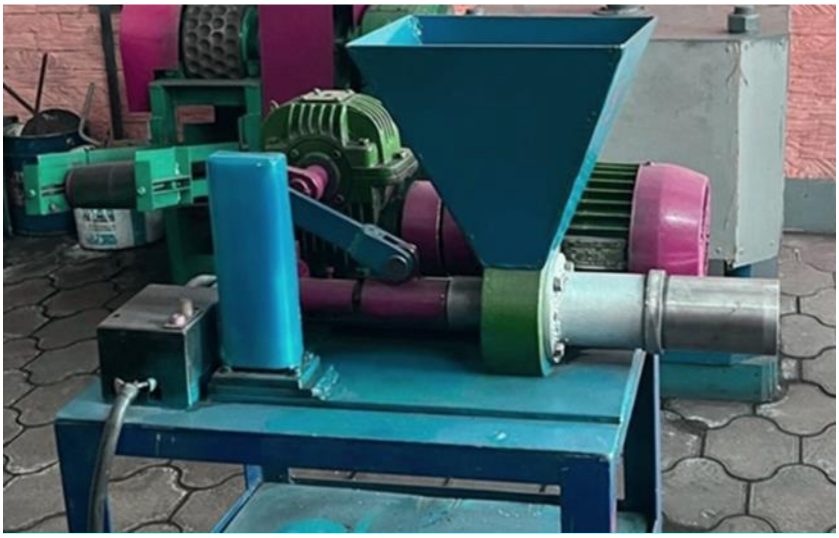

Figure 2.
Laboratory press.

The briquette had the following technical characteristics:
- Fraction of coal, spent anode material, coal pitch – 0-3 mm;
- The amount of coal is 50 %.
- The number of spent anode materials is 30 %.
- The coal pitch is 20 %.
- Diameter – 50 mm.
- Length – 50 mm.
- The mass of the finished briquette is 114 g.

During dry mixing, these components should be evenly distributed relative to each other. Further mixing is carried out in the working cavity of the mixer with a heating system, where the briquette mass is heated to a temperature of 150^0C. The duration of heating depends on the physico-chemical properties of the binder and the intensity of mixing. The heat passing through the stirred mass heats the components of the mixture, causing the coal pitch particles to melt and envelop the coal particles and particles of the spent anode material. The mass should not crumble, be viscous, but not liquid, and should form a well-defined lump when compressed. The mixing time was 10 minutes.

According to this concept, with a technologically sufficient degree of mixing of the particles, the binder completely envelops the solid particles of the filler (coal) and the concentrator (spent anode material) with a film of a certain thickness, resulting in durable briquettes. Figure 3 shows the resulting briquettes.

Figure 3.
Coal briquettes.

The resulting briquettes were then coked using a laboratory technique that mimics the standard industrial process of thermal decomposition of carbon-containing raw materials in the absence of oxygen. Coking was carried out in an airtight laboratory coking tank made of heat-resistant steel, equipped with a discharge tube with a rubber nipple valve to remove volatile pyrolysis products (see Figure 4).

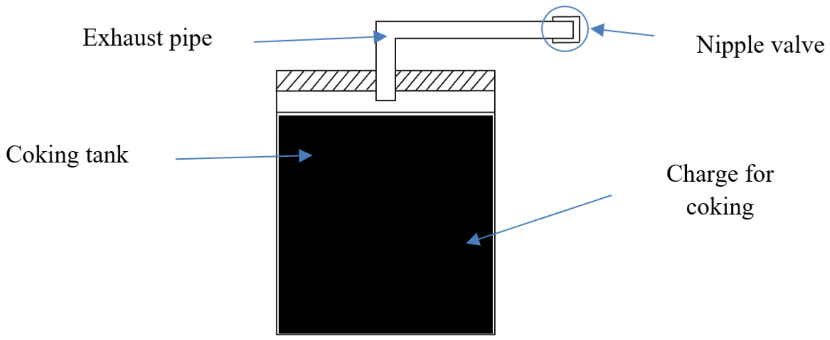

Figure 4.
Coking tank.

The coking tank was placed in an electric SNOL muffle furnace with programmable temperature control up to 1150°C. The coking process was carried out according to the following temperature regime:

- Heating from 25 to 1000 °C at a rate of ~10-12 °C/min (average 90 minutes);
- Isothermal exposure at 1000 ° C for 60 minutes to complete the processes of degassing and formation of the coke structure;
- Cooling - the furnace was turned off, and the coke was left inside until it gradually cooled.

Cooling was carried out naturally in a closed container at ambient temperature, which ensured a slow decrease in temperature and prevented oxidation of the coke. Complete cooling to a temperature of no more than 50°C took approximately 5 hours; this cooling mode made it possible to prevent oxidation and preserve the structural characteristics of the resulting coke. Afterward, the samples were extracted for subsequent physico-chemical analysis. The selected temperature and time regime ensure the stable formation of the coke structure in a laboratory setting.

Figure 5 shows the coke samples. The resulting coke was a porous structure, and the average size was 3-5 mm, which meets the requirements for coke used in sintering production.

Figure 5.
The prepared coke samples.

The chemical composition of the resulting coke is shown in Table 1.

Table 1.
Chemical composition of coke.

Carbon (C), %	Sulfur (S), %	Ash Content (Ash), %	Volatiles, %	Moisture (Wr), %
85	0.9–1.1	19.0	1.5-2.5	≤ 1

The resulting coke is characterized by a high carbon content (85%) and low humidity (<1%), which confirms its fuel suitability. Despite the increased values of ash content (19%) and sulfur (0.9–1.1%), this composition is acceptable for use in sintering production. The increased ash content and sulfur content are due to the use of high-ash Ekibastuz coal and spent anode material as residues of electrolysis production of aluminum, containing sulfur compounds in the charge.

The electrical resistivity of coke is an important parameter because it is related to its thermal conductivity and reactivity in the agglomeration process. Although the agglomeration process itself is mainly thermal, the coke thermal power plant affects the combustion efficiency and heat distribution in the agglomeration charge [26-29]. Figure 6 shows the laboratory installation diagram that was used to determine the specific electrical resistance of coals [30].

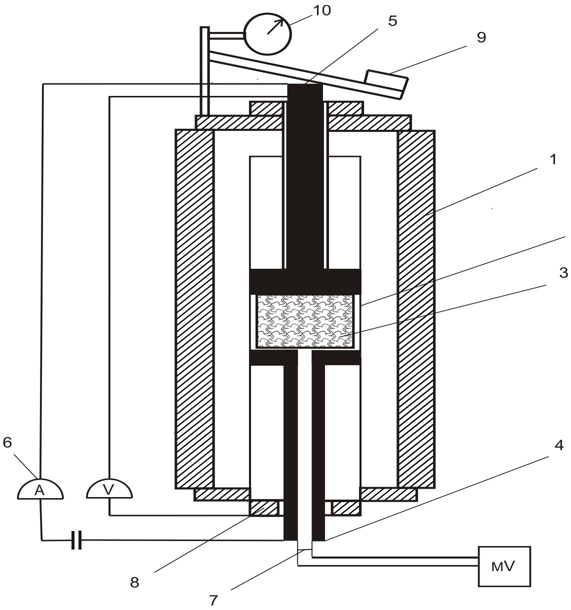

Figure 6.
Installation for determining the resistivity of materials.

The experimental installation consists of a heating furnace (1) containing a cylinder (2) made of an electrically insulating material. The working space of the cylinder was filled with the studied coal (3), with a layer height of 40 mm and a grain size of 3-6 mm. The working volume of the cylinder was limited from below by fixed molybdenum current-carrying electrodes (4), supplied with voltage from a transformer with current measurement by an ammeter (6). A pressure of 0.4 kg/cm^2 was applied to the upper movable molybdenum electrode (5) and the test material through a load (9). The resistance was measured using an ammeter-voltmeter.

The resistance of transient contact connections is eliminated by using a potentiometric method for measuring the voltage drop in the test area, which is limited by potentiometric rings connected to a voltmeter. To prevent the formation of micro-arcs between particles, the applied voltage should not exceed 1.5-2.0 V.

The electrical resistivity is calculated using Equation 1 [30]:

$$\rho = \frac{\Delta U \cdot S}{I \cdot H}, \quad (1)$$

where ΔU: voltage drop in the test area, S: the cross-sectional area of the cylinder, H: the distance between the upper and lower electrodes.

4. Results

Thermal analysis of Ekibastuz coal, spent anode material, and coal pitch was conducted to determine the temperature ranges for producing coke with optimal characteristics.

Figures 7-10 show the results of experiments on burning the samples inside the Derivatograph furnace. Thermal analysis was performed for all components separately and in a mixture.

The figures show the relationships between the mass of the sample (m) (TG curve), the rate of mass change (dm/dt) (DTG curve), and the temperature difference between the sample and the reference (Δt) (DTA curve) as a function of the heating temperature (t) [31, 32]. For a single-stage non-isothermal reaction, two key points on the thermogravimetric curve can be distinguished: the temperature at which decomposition begins, where the mass change becomes noticeable on thermal weights, and the final temperature, where the mass change reaches its maximum, indicating the completion of the reaction. This suggests optimal temperature conditions for conducting thermal processes in practice.

In the thermal analysis of coal from the Ekibastuz deposit (initial mass 62.5 mg, residue mass 10.6 mg), heating of the sample begins at a temperature of 25 °C (see Figure 7). A decrease in its mass (TG curve) was observed at the beginning of heating. At the same time, in the temperature range of 25-100 °C, adsorbed water was removed from the sample, i.e. the sample is dried. After drying at a temperature above 100 °C, a slight increase in the mass of the sample occurs with a maximum at 250 °C, which, taking into account the heating medium (air), can be explained by the course of oxidation reactions of coal, which are accompanied by the introduction of oxygen atoms into its structure. Such processes (an increase in the mass of the sample when it is heated) are characteristic of low-temperature heating of high-molecular organic compounds in oxidizing media.

When a sample of Ekibastuz coal is heated above 130°C, the thermal decomposition of fragments of its molecular structure begins with the cleavage of low-molecular-weight compounds from the carbon matrix, passing into the gas phase. This is accompanied by a decrease in the mass of the sample, which increases sharply at temperatures above 400°C, as observed from the TG curve. The released gaseous products in the air begin to burn, causing an increase in temperature in the sample area. This leads to the emergence of exothermic processes that occur with the release of heat in the temperature range of 300–500°C. At temperatures above 450°C, the intensity of exothermic effects begins to decrease, which is associated with a slowdown in gas formation and the predominance of coke residue combustion over the combustion of gaseous products. At the same time, the mass of the residue from the burning of Ekibastuz coal in the furnace of the derivatograph was 10.6 mg.

The general characteristic of the derivatogram indicates a multi-stage process of thermal decomposition of coal, starting from drying and ending with the complete decomposition of the carbon structure with the release of volatile products.

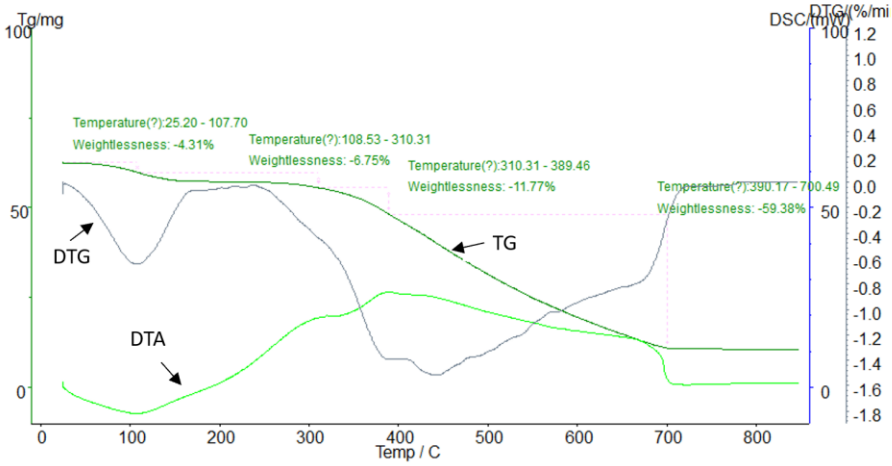

Figure 7.
Ekibastuz coal trifle.

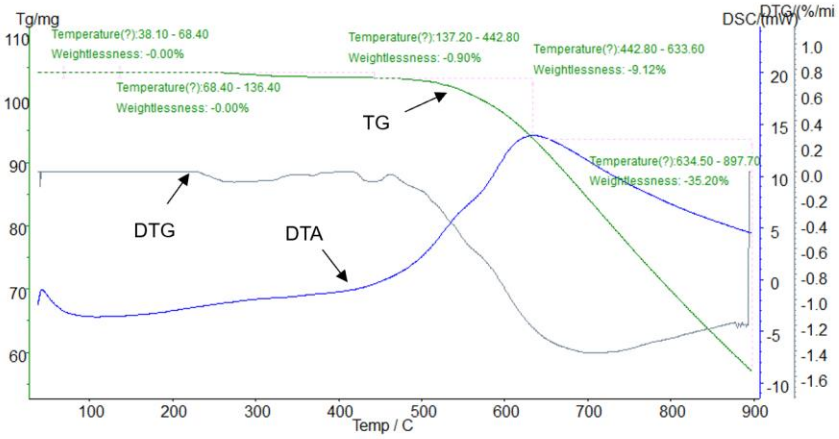

Figure 8.
Spent anode material, JSC Kazakhstan Electrolysis Plant.

When conducting a differential thermal analysis of a spent anode material weighing 104.29 mg, an initial decline peak is observed (see Figure 8), indicating heat absorption, followed by an increase in the curve to 440 °C with almost no weight loss, confirming its relationship to the graphite structure. A further increase in temperature, with the highest exothermic peak at 632 °C, is accompanied by a small mass loss of about 9% and the release of volatile substances. An additional endothermic decline shows a uniform change in the structure of the carbon component, with the highest percentage of weight loss, totaling 45.22%.

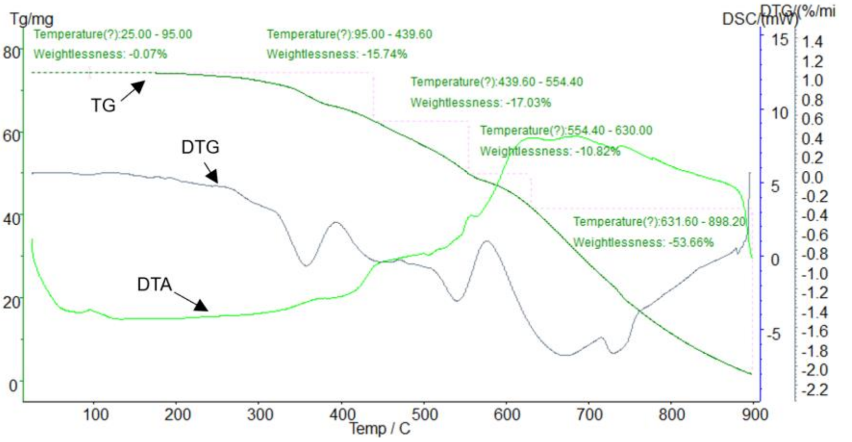

Figure 9.
Coal pitch, JSC Kazakhstan Electrolysis Plant.

The curves of the DTA-coal pitch are accompanied by insignificant peaks up to 444°C, characterized by the release of hygroscopic moisture (see Figure 9). Further growth in peaks at 554°C and 627°C indicates the release of volatile substances and restructuring of the carbon component's structure. Further heating is characterized by insignificant peaks with the release of the resinous component. The initial weight was 74.26 mg, and the total loss was 72.13 mg (97.32%).

For a qualitative assessment of the possibility of using coal fines from the Ekibastuz deposit in the production of sintering coke, the composition of the charge was prepared with the following proportions of the components used, with a fraction of 0–3 mm:

- Coal change – 50%;
- Spent anode material – 30 %;
- Coal pitch – 20 %;
- The total weight of the suspension was 59.31 mg.

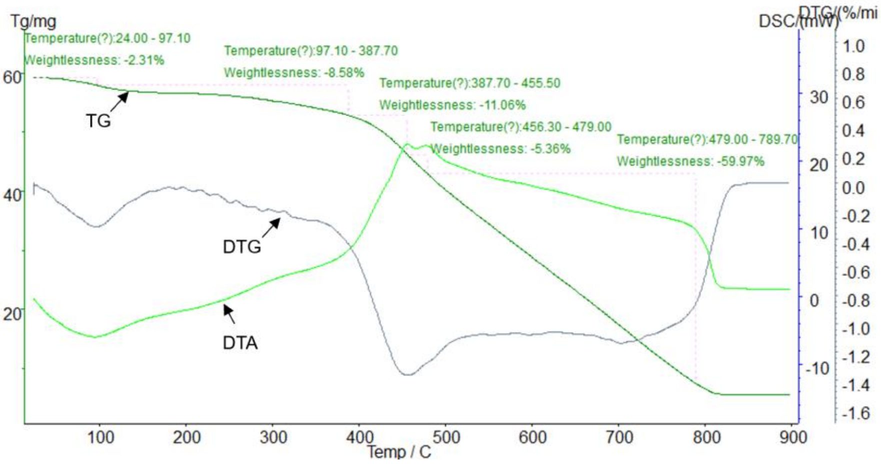

Figure 10.
Charge for coking.

Figure 10 shows the beginning of the process of thermal analysis of the charge for coking is accompanied by heat absorption and a small endothermic peak indicating the removal of hydrated moisture at 100 °C. Further heating is accompanied by the release of volatile components. The process of changing the structure of the carbon component begins at a temperature of 387°C, with a transient thermal effect peaking at 455.50°C. Subsequently, there is a slight decrease in the endothermic curve, indicating the course of destructive processes involving the destruction of semi-coke and the release of heavy resin fractions. The subsequent growth and gradual decline of the curve to a specified temperature suggest the final restructuring of the structure and the formation of coke. The weight loss was 51.96 mg, representing 87.28%.

Table 2.
Distribution of mass losses of gaseous products in specified temperature ranges according to derivatograms (Figure 7 – 10).

Temperature, °C	Coal change		Temperature, °C	Spent anode material		Temperature, °C	Coal pitch		Temperature, °C	The resulting coke	
	mg	%		mg	%		mg	%		mg	%
25-108	2.50	4.31	38-68	0	0	25-95	0.05	0.07	24-97	1.37	2.31
108-310	4.22	6.75	68-136	0	0	95-439	11.76	15.74	97-388	5.12	8.58
310-389	7.36	11.77	136-442	0.96	0.90	439-554	12.58	17.03	388-456	6.64	11.06
390-700	37.12	59.38	442-633	9.61	9.12	554-630	8.03	10.20	456-479	3.18	5.36
700-800	0.51	0.32	634-898	93.72	35.20	631-898	39.71	53.66	479-790	35.65	59.97
Losses	51.96	82.53	Losses		45.22	Losses	72.13	97.32	Losses	51.96	87.28

Table 2 shows the distribution of mass losses of gaseous products in the specified temperature ranges according to derivatograms, (see Figures 5 to 8). The temperature of the test material was measured continuously using a BP-type thermocouple (7) placed in the cylinder opening through the lower electrode. Water cooling of the furnace body was maintained using a refrigerator (8). The rate of temperature increase was 17-20 degrees per minute, which corresponds to the heating rate of the charge in electric furnaces. The change in the height of the reducing agent layer was recorded by the indicator (10). To compare the properties of the coke under study, the electrical resistivity values of Chinese and Magnitogorsk coke (Russia), which are most commonly used in metallurgical production, were obtained from literature sources [33, 34]. China and Russia are the main exporters of metallurgical coke in the Central Asian market, including Kazakhstan. Comparing the types of coke widely used in Kazakhstan allows us to objectively assess the prospects of our coke for real-world applications, including in sintering production or as a reducing agent. The data is shown in Figure 11 and Table 2.

Table 2 and Figure 11 show the data of the coke obtained by us in comparison with the reducing agents of China and Russia. The data of the obtained coke, in comparison with other reducing agents, have significantly low resistivity indicators, which fully meet the requirements of sintering production.

The coke under study differs significantly in its electrical characteristics from both Chinese and Magnitogorsk coke, especially at low temperatures (20-500°C). At room temperature (20°C), the resistivity of the studied coke is only 0.21 ohm·cm, which is much lower than that of Magnitogorsk coke (4.06 ohm·cm) and Chinese coke (5.53 ohm·cm). This indicates a higher electrical conductivity of the material under study at low temperatures, which may be due to its microstructure and phase composition features.

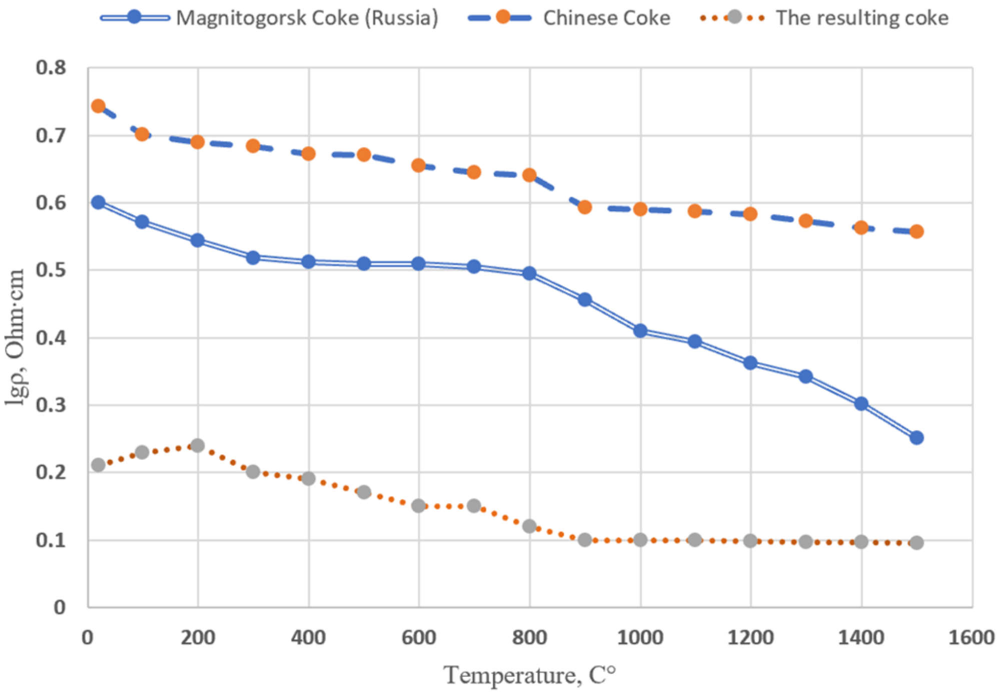

Figure 11.
The values of the resistivity of the studied coke, Chinese coke and Magnitogorsk coke.

With increasing temperature, all three types of coke demonstrate a decrease in resistivity, which is typical for carbon materials, since their electrical conductivity increases when heated. However, in the studied coke, the decrease in resistivity occurs more sharply compared to Chinese and Magnitogorsk cokes. For example, at a temperature of 900°C, the resistivity of the studied coke is 0.1 ohm·cm, which is lower than that of Chinese coke (3.91 ohm·cm) and Magnitogorsk coke (2.86 ohm·cm).

Table 3.
Comparative values of resistivity of the studied coke, Chinese coke and Magnitogorsk coke.

Temperature, C	Electrical Resistivity, ohm-cm		
	Magnitogorsk Coke (Russia)	Chinese Coke	The resulting coke
20	4.06	5.53	1.62
100	3.73	5.02	1.69
200	3.50	4.89	1.73
300	3.30	4.82	1.58
400	3.25	4.70	1.54
500	3.23	4.69	1.47
600	3.23	4.51	1.41
700	3.20	4.41	1.41
800	3.12	4.37	1.31
900	2.86	3.91	1.25
1000	2.57	3.89	1.25
1100	2.48	3.86	1.25
1200	2.30	3.82	1.25
1300	2.20	3.74	1.25
1400	2.00	3.65	1.25
1500	1.78	3.60	1.24

5. Discussion

Figure 11 and Table 3 show that at high temperatures (1000-1500 °C), the resistivity of the coke under study stabilizes at the level of 0.096–0.1 Ohm · cm, which indicates its good stability at high temperatures. This property is useful in high-temperature processes such as agglomeration and blast furnace melting, where it is necessary to maintain stable electrophysical characteristics under extreme thermal loads. Chinese coke and Magnitogorsk coke exhibit higher resistivity values across the entire temperature range. Although both types of coke also show a decrease in resistance with increasing temperature, their values remain significantly higher, which may indicate differences in carbon structure, impurity content, and physico-chemical properties. The electrical conductivity of the coke under study is significantly higher at all temperature conditions, which can contribute to more efficient conduction of heat and electricity in metallurgical processes. This makes it promising for use in high-temperature processes requiring high thermal conductivity and resistance to thermal shock. Based on comparative data on the electrical resistivity of other types of coke (Figure 9 and Table 2), the coke under study has highly conductive electrical properties at low and high temperatures, which makes it a competitive material for use in metallurgical processes such as agglomeration and blast furnace smelting.

A decrease in the resistivity of the coke under study at high temperatures indicates its stable and improved physico-chemical characteristics, which can increase overall production efficiency.

Figure 9 and Table 2 show low values of the resistivity, which indicates the improvement of the electrical conductivity of the resulting coke, which was most likely caused by the following conditions:

- Spent anode materials, due to the high content of graphitized carbon, contributed to the improvement of the conductivity of coke;
- The product was completely coked, which provided a complete release of volatile substances that could contribute to an increase in resistivity.

The electrical resistivity of sintering coke plays an important role in the agglomeration process, affecting heat distribution, reactivity, and the quality of the agglomerate. Low resistivity is preferable, as it contributes to efficient combustion and the maintenance of optimal temperature in the charge [35]. Figure 6 shows the thermal details of the spent anode material, which, as a structure and behavior is close to graphite, limiting its 100 % use and being of interest as a filler to increase the carbon content. The acceptable content of the spent anode material in the charge should not exceed 30 %.

The heat of combustion is the most important indicator of the quality of energy fuel and characterizes the thermal value of coals [36]. The work also determined the calorific value of coal and the resulting coke by calculating the elemental composition of coal [37]. It was revealed that the calorific value of briquettes with a concentrator in the form of spent anode materials and a binder in the form of coal pitch is higher than Ekibastuz coal by 20-40% and is $-\Delta H^0_{combustion}$ = 6940,5 kcal/kg, which indicates the high energy potential of the briquette. Spent anode materials contain pure carbon, which has a high calorific value comparable to coal, which contributes to an overall increase in the calorific value of the briquette. Coal tar, in turn, as a binder, increases the mechanical strength of briquettes because the softening temperature of the pitch is 60-150 °C (depending on the grade), and also has a high adhesive ability, which ensures uniform binding of coal particles during the briquetting process. Coal tar contains 85-95 % carbon, which makes it an effective component for increasing the carbon content of briquettes. Also, the calorific value of pitch is about 7500-8000 kcal/kg. This makes it an excellent addition to fuel materials, as the pitch not only serves as a binder but also adds additional heat during combustion [38]. The calorific value of the briquette, equal to 6840.8 kcal/kg, indicates that the briquette is a highly efficient fuel capable of replacing high-quality coal in the sintering process or other metallurgical applications. Such a briquette is suitable for processes requiring high temperatures, for example, for agglomeration or blast furnace melting, as it will provide sufficient heat for melting and maintaining the temperature regime. The resulting coke from such briquettes has high mechanical strength, good physical and chemical characteristics, and good reactivity, which will contribute to the effective support of melting processes [39].

6. Conclusion

6.1. Main Findings

The conducted experimental and analytical studies have confirmed the possibility of effectively producing metallurgical coke from a briquetted mixture of man-made and carbon-containing wastes: fines of Ekibastuz coal (50%), spent anode material from electrolysis production of aluminum (30%), and coal pitch (20%). The use of this charge not only allows for the utilization of valuable secondary resources but also results in a product with physico-chemical characteristics that meet the requirements of sintering industries.

- A mixture of coal fines, spent anode materials, and coal pitch can produce high-quality metallurgical coke, indicating a promising method for agglomeration production.
- The lower electrical resistivity of the resulting coke, particularly in comparison to existing cokes (e.g., Magnitogorsk and Chinese coke), suggests enhanced thermal properties, which could lead to more efficient sintering processes in metallurgy.
- The briquettes' high calorific value indicates their suitability as an efficient fuel for high-temperature applications, potentially replacing traditional coke and supporting sustainable production practices.
- The successful coking and favorable physicochemical characteristics suggest that utilizing man-made waste in coke production can not only optimize performance in metallurgical processes but also contribute to more sustainable resource use.

6.2 Limitations

- The study was conducted under laboratory-scale conditions, which may not fully capture the complexities of industrial-scale coke production.
- Some performance indicators, such as long-term behavior in sintering plants and environmental emissions during full-scale processing, were not evaluated.
- The ash and sulfur content, while acceptable, may require further refinement or treatment to meet stricter metallurgical standards.

6.3 Future Research Directions

- Scaling the process for pilot and industrial testing to assess operational feasibility under production conditions.
- Investigating alternative binders or additive materials to reduce ash content and further improve mechanical and thermal properties.
- Evaluating the environmental and economic impacts of large-scale implementation, including life cycle assessment and cost-benefit analysis.
- Exploring process integration opportunities within existing metallurgical plants to enable closed-loop, waste-to-resource conversion systems.

.

References

[1] E. V. Karunova, V. L. Vikulov, and O. A. Kalko, "The use of a fine coke additive in the coal charge to obtain high-quality coke," *Transactions of the Kola Science Centre of RAS. Series: Engineering Sciences,* vol. 14, no. 1, pp. 116–121, 2023. https://doi.org/10.37614/2949-1215.2023.14.1.021

[2] A. M. Bizhanov and C. Aubertot, "Sintering and briquetting synergy in blast furnace smelting," *Metallurgist,* vol. 65, no. 7, pp. 699-712, 2021. https://doi.org/10.1007/s11015-021-01208-8

[3] L. B. Tolymbekova, K. S. Yersain, and A. A. Kamenov, "Technologies for the production of non-annealed pellets," in *Defect and Diffusion Forum*, 2021, vol. 410: Trans Tech Publ, pp. 313-317.

[4] H. Ma, J. Zhao, L. Pin, J. Zhou, and J. Liu, "Cooperative treatment and resource utilization of municipal solid waste by industrial coke ovens: Effects of doping ratio and management," *BioResources*, vol. 19, no. 2, p. 3668, 2024. https://doi.org/10.15376/biores.19.2.3668-3680

[5] A. Aubakirov, A. Kaliakparov, and L. Tolymbekova, "Determination of the quality of special coke as a result of heat treatment of coal from the Shubarkol field," *Kompleksnoe Ispolzovanie Mineralnogo Syra= Complex use of Mineral Resources,* vol. 326, no. 3, pp. 96-106, 2023. https://doi.org/10.31643/2023/6445.33

[6] J. Krupanek, G. Gałko, M. Sajdak, and M. Pogrzeba, "Comparison of bio-coke and traditional coke production with regard to the technological aspects and carbon footprint considerations," *Energies*, vol. 17, no. 12, p. 2978, 2024. https://doi.org/10.3390/en17122978

[7] V. Solodov, T. Cherkasova, N. Kolmakov, S. Subbotin, and Y. Radchenko, "Research of characteristics of PJSC 'Koks' coal and coke dust fuel briquettes," *E3S Web of Conferences,* vol. 134, pp. 2–7, 2019. https://doi.org/10.1051/e3sconf/201913402007

[8] B. Xuegong and X. Kuangdi, "Agglomeration of Iron ores," in The ECPH encyclopedia of mining and metallurgy, K. Xu Ed. Singapore: Springer Nature Singapore, 2022, pp. 1-2. https://doi.org/10.1007/978-981-19-0740-1_937-1

[9] A. U. Khan, Q. M. Jan, M. Abas, K. Muhammad, Q. M. Ali, and D. Zimon, "Utilization of biowaste for sustainable production of coal briquettes," *Energies*, vol. 16, no. 20. https://doi.org/10.3390/en16207025

[10] A. A. Adeleke, J. K. Odusote, P. P. Ikubanni, A. S. Olabisi, and P. Nzerem, "Briquetting of subbituminous coal and torrefied biomass using bentonite as inorganic binder," *Scientific Reports*, vol. 12, no. 1, p. 8716, 2022. https://doi.org/10.1038/s41598-022-12685-52

[11] M. Wu, K. Wei, J. Jiang, B. B. Xu, and S. Ge, "Advancing green sustainability: A comprehensive review of biomass briquette integration for coal-based energy frameworks," *International Journal of Coal Science & Technology*, vol. 12, no. 1, p. 44, 2025. https://doi.org/10.1007/s40789-025-00779-0

[12] L. Florentino-Madiedo, E. Díaz-Faes, and C. Barriocanal, "Reactivity of biomass containing briquettes for metallurgical coke production," *Fuel Processing Technology*, vol. 193, pp. 212-220, 2019. https://doi.org/10.1016/j.fuproc.2019.05.017

[13] T. I. Chernyshova, E. P. Naboko, and N. V. Alpatov, "Technologies of utilization of carbon-containing waste from coke chemical production in order to obtain fuel briquettes," *Current Issues of Modern Science*, vol. 15, no. 1, pp. 144–152, 2015.

[14] R. Alvarez, C. Barriocanal, M. A. Díez, J. L. G. Cimadevilla, M. D. Casal, and C. S. Canga, "Recycling of hazardous waste materials in the coking process," *Environmental Science & Technology*, vol. 38, no. 5, pp. 1611-1615, 2004. http://dx.doi.org/10.1021/es030077y

[15] L. B. Pavlovich, N. Y. Solovyova, E. D. Pavlovskaya, and V. M. Strakhov, "Using polymer waste in coke production," *Coke and Chemistry*, vol. 59, no. 8, pp. 287-295, 2016. http://dx.doi.org/10.3103/S1068364X16080068

[16] M. A. Diez, R. Alvarez, and J. L. G. Cimadevilla, "Briquetting of carbon-containing wastes from steelmaking for metallurgical coke production," *Fuel*, vol. 114, pp. 216-223, 2013. https://doi.org/10.1016/j.fuel.2012.04.018

[17] A. V. Rasskazova, "Substantiation of rational parameters of brown coal briquetting using mechanical activation of fuel components," PhD Thesis Abstract, Khabarovsk, pp. 683–687, 2014.

[18] J. Liu, Y. Yuan, J. Zhang, Z. He, and Y. Yu, "Combustion kinetics characteristics of solid fuel in the sintering process," *Processes*, vol. 8, no. 4, pp. 2-16. https://doi.org/10.3390/pr8040475.

[19] E. S. Dostov, S. G. Korotkov, and I. V. Anishchenko, "The influence of the fractional composition of coal on the quality of coke," *Bulletin of the Siberian State Industrial University*, vol. 3, no. 29, pp. 36–40, 2019.

[20] L. Zhou, Z. Yao, K. Sun, Z. Tian, J. Li, and Q. Zhong, "Methodological review of methods and technology for utilization of spent carbon cathode in aluminum electrolysis," *Energies*, vol. 17, no. 19. https://doi.org/10.3390/en17194866

[21] A. T. Ordabaeva, Z. M. Muldakhmetov, M. G. Meiramov, S. V. Kim, and Z. I. Sagintaeva, "Production of pitch from coal tar of the coke chemical production "qarmet"," *Molecules*, vol. 30, no. 7. https://doi.org/10.3390/molecules30071441

[22] L. Dong, X. Huang, J. Ren, L. Deng, and Y. Da, "Thermogravimetric assessment and differential thermal analysis of blended fuels of coal, biomass and oil sludge," *Applied Sciences*, vol. 13, no. 19, pp. 1-16. https://doi.org/10.3390/app131911058

[23] E. Ghanbari, S. J. Picken, and J. H. van Esch, "Analysis of differential scanning calorimetry (DSC): determining the transition temperatures, and enthalpy and heat capacity changes in multicomponent systems by analytical model fitting," *Journal of Thermal Analysis and Calorimetry*, vol. 148, no. 22, pp. 12393-12409, 2023. https://doi.org/10.1007/s10973-023-12356-1

[24] N. F. Z. Asyqin, J. M. Saiter, S. I. A. Halim, R. Lucas, and C. H. Chan, "Thermal analysis: Basic concept of differential scanning calorimetry and thermogravimetry for beginners," *Chemistry Teacher International*, vol. 3, no. 2, pp. 59-75, 2021. https://doi.org/10.1515/cti-2020-0010

[25] S. Kim *et al.*, "Influence of coal heat treatment parameters on physical-chemical properties of smokeless fuel," *Вестник Карагандинского университета. Серия: Химия*, vol. 4, no. 92, pp. 62-67, 2018. https://doi.org/10.31489/2018ch4/62-67

[26] G. R. Surup, T. A. Pedersen, A. Chaldien, J. P. Beukes, and M. Tangstad, "Study on the correlation between coal property parameters and its pyrolysis heat absorption," *Journal of the Energy Institute*, p. 120, 2025.

[27] A. A. Akberdin, A. S. Kim, L. B. Tolymbekova, and R. B. Sultangaziyev, "Development of technology for producing complex Boron-containing aluminum-silicon ferroalloy," *Metallurgist*, vol. 67, no. 8, pp. 749-756, 2023.

[28] G. R. Surup, T. A. Pedersen, A. Chaldien, J. P. Beukes, and M. Tangstad, "Electrical resistivity of carbonaceous bed material at high temperature," *Processes*, vol. 8, no. 8, pp. 1-22, 2020. https://doi.org/10.3390/pr8080933

[29] O. Bazaluk *et al.*, "Metallurgical coke production with biomass additives: Study of biocoke properties for blast furnace and submerged arc furnace purposes," *Materials*, vol. 15, no. 3. https://doi.org/10.3390/ma15031147.

[30] G. M. Zhilo and V. I. Alexandrov, "Methods of measuring the specific electrical resistance of raw materials and materials of chemical electrothermy," *Obzornaya Informatsiya*, p. 16, 1986.

[31] M.-g. Yu, Z. Yan-min, and L. Chang, "Thermal analysis of kinetics of coal oxidation," *Procedia Earth and Planetary Science*, vol. 1, no. 1, pp. 341-346, 2009. https://doi.org/10.1016/j.proeps.2009.09.054

[32] W. Wang *et al.*, "Thermal analysis of coke-H2O gasification reaction non-isothermal kinetic study," *International Journal of Hydrogen Energy*, vol. 139, pp. 237-246, 2025. https://doi.org/10.1016/j.ijhydene.2025.05.266

[33] L. Kieush, J. Schenk, A. Pfeiffer, A. Koveria, G. Rantitsch, and H. Hopfinger, "Investigation on the influence of wood pellets on the reactivity of coke with CO2 and its microstructure properties," *Fuel*, vol. 309, p. 122151, 2022. https://doi.org/10.1016/j.fuel.2021.122151

[34] P. A. Eidem, M. Tangstad, and J. A. Bakken, "Determination of electrical resistivity of dry coke beds," *Metallurgical and Materials Transactions B*, vol. 39, no. 1, pp. 7-15, 2008. https://doi.org/10.1007/s11663-007-9105-7

[35] D. Miroshnichenko *et al.*, "Electrical resistance as an aggregate characteristic of coke properties for electrochemical and coke production," *Electrochem*, vol. 5, no. 2, pp. 258-273. https://doi.org/10.3390/electrochem5020016

[36] A. N. Alekhnovich, "Estimating the heating value of coals based on the composition," *Power Technology and Engineering*, vol. 53, no. 6, pp. 724-730, 2020. https://doi.org/10.1007/s10749-020-01147-5

[37] S. m. f. GOST 30354-2013, *Determination of the highest heat of combustion by calculation of the elemental composition*. Moscow, Russia: Standartinform, 2013.

[38] G. P. Khokhlova, C. N. Barnakov, L. M. Khitsova, and V. Y. Malysheva, "Features of thermal conversion of coal tar in conditions of low-temperature catalytic graphitation under different heat treatment modes," *Bulletin of the Kuzbass State Technical University*, vol. 1, no. 101, pp. 89–94, 2014.

[39] Y. S. Abdrakhmanov, A. V. Bogomolov, P. O. Bykov, and A. B. Kuandikov, "Thermal capacity of enriched fuel briquets produced from the fine of Ekibastus coal," *International Journal of Engineering Technologies and Management Research*, vol. 4, no. 9, pp. 49–63, 2017.