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Research Article

Study of the Granulability of Brown Coal Using Inorganic Binders

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ABSTRACT

The aim of this research is to develop and evaluate a granulation technology for Kyrgyzstan's brown coal using inorganic binders, with the goal of improving its physical and mechanical properties. Experiments were conducted using a laboratory drum granulator with inorganic binders, preceded by analysis of physical and chemical properties, including elemental composition, ash content, calorific value, and particle size, of samples from the Kozho-Kelen and Kyzyl-Bulak deposits. Kyrgyzstan holds 24 billion tonnes of brown coal reserves (2.3 billion explored), with 2023 production reaching 4 million tonnes. Raw coal is characterised by moisture content of 40-50%, ash content of 12-15%, calorific value of 8-12 MJ/kg, and fine fractions (<5 mm) comprising 65-70%, with dust losses of up to 30%. Granulation with 10% inorganic binders raised the granulation coefficient to 85-95%, producing 4-8 mm granules with compressive strength up to 2.5 MPa (a 212% increase with Portland cement), reduced abrasiveness by 73% (to 12.3%), increased calorific value to 11.2 MJ/kg, and decreased porosity from 35% to 15%. The technology outperforms analogues from China (2.2 MPa, 18% ash) and Australia (2.0 MPa, 15% abrasiveness). Economic assessment for a 10,000 tonne/year operation shows savings of 2,500 tonnes of coal, an economic effect of USD 125,000, and a payback period of 1.5 years. At 50,000 tonnes/year, projected profit reaches USD 500,000. The technology raises brown coal value by 30-40%, supports environmental objectives, and aligns with Kyrgyzstan's national sustainable development priorities. The developed granulation technology offers significant economic and environmental benefits, supporting the sustainable development of the country's coal industry and reducing material losses and environmental pollution.

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1. INTRODUCTION

Agglomeration of fine coal particles is the process of forming larger granules through the interaction of physical and chemical forces. Fine particles, typically under 5 mm, adhere due to moisture or binder presence, with forces such as Van der Waals and capillary forces playing a key role. When binders like bentonite or Portland cement are added, they chemically bond with the coal particles, enhancing cohesion and providing stability. The binders facilitate the formation of strong calcium bridges or hydration products, increasing compressive strength and reducing porosity. This results in stable granules capable of withstanding mechanical stress during transport and storage, ensuring minimal breakage and dust formation.

Despite its vast global reserves, brown coal remains a low-grade raw material due to several unfavourable characteristics: high moisture content (up to 50%), low calorific value (8-12 MJ/kg) and a significant tendency to dust formation, leading to losses of up to 30% of material during extraction, transportation and storage (Cheng et al., 2024; Valujeva et al., 2024). These properties significantly limit their use in energy and industry, increasing processing costs and exacerbating environmental problems associated with emissions of fine coal dust. In Kyrgyzstan, where brown coal reserves are estimated at 24 billion tonnes, of which 2.3 billion tonnes are explored, these coals are a strategic resource for the energy sector and chemical industry, especially in conditions of limited access to alternative fuels (Temirbaeva et al., 2024; Babak et al., 2021). However, the lack of modern processing technologies, such as granulation or briquetting, leads to material losses, a reduction in its market value and increased environmental impact, including air and soil pollution from coal dust. The development of effective granulation methods using affordable inorganic binders, such as bentonite clay, Portland cement and hydrated lime, can minimise these problems, improve the transportability, energy efficiency and environmental safety of brown coal, and create prospects for its commercialisation on domestic and international markets. This study was initiated by the need to address these issues for Kyrgyzstan's brown coal, with a focus on the local deposits of Kozho-Kelen (Osh region) and Kyzyl-Bulak (Jalal-Abad region), to propose an economically viable, technologically accessible and environmentally sustainable processing technology adapted to the conditions of small and medium-sized enterprises in the country.

For the purpose of this study, granules are defined as small, irregularly shaped particles formed by agglomeration, typically with a size range of 4-8 mm, which are stable enough for transportation and combustion. Pellets are compact, uniform, cylindrical forms of coal, usually produced by extrusion or compression, designed for efficient combustion and handling. Briquettes are larger, denser, compressed forms of coal, often used for industrial heating, and may include additional binders to improve strength and reduce dust. In this study, the focus is on granules, formed using inorganic binders to enhance their physical properties for energy use. The issue of brown coal processing was actively studied between 2020 and 2025. Research into coal agglomeration highlights the importance of binders for improving the physical and mechanical properties of granules and briquettes. Tulepov et al. (2021) studied the briquetting of Kazakh coal with inorganic additives, showing that clay increases the strength of briquettes to 1.5-2 MPa, but requires optimisation to reduce ash content. Omarov et al. (2025) investigated the use of brown coals to produce humic fertilisers, revealing their chemical potential, but did not address aspects of granulation for energy purposes. Andriyko et al. (2024) analysed bentonite-carbon sorbents, establishing their high adsorption capacity, but noted their limited mechanical strength (up to 1.8 MPa), which requires further research for energy applications. Makhammadjanov (2021) studied the thermal conductivity of coal mixtures, emphasising the need to increase calorific value to improve energy properties. Lalah et al. (2022) focused on the environmental aspects of coal processing, highlighting the problem of fine particle emissions, which is relevant for Kyrgyzstan.

Erkinbaeva and Shakirbaev (2025) identified the presence of rare earth elements in brown coal in Kyrgyzstan, increasing its value, but did not solve the problem of dust formation. Skaczko and Guminski (2020) investigated granular activated carbons with different binders, noting that bentonite increases porosity while reducing calorific value. Angalakuditi et al. (2024) studied the rheological properties of granular mixtures, emphasising the importance of moisture content (20-30%) for effective agglomeration. Kocherov et al. (2024) analysed the physicochemical properties of granules from coal mining waste, showing that inorganic binders increase strength to 2 MPa, but their applicability to brown coal requires clarification. Lomunyak et al. (2024) studied organic binders for coal briquettes, but their high cost limits their application in Kyrgyzstan. These studies highlight the need for further research into the granulation of brown coal, addressing local conditions and economic feasibility. Existing work does not fully address the problem of processing Kyrgyzstan's brown coal, given its high moisture content, ash content and the limited resources of local enterprises. Gaps include a lack of data on the use of inorganic binders for local coals, the absence of optimised models for predicting pellet quality, and limited attention to the economic efficiency of technologies for small enterprises. This study fills these gaps by proposing a granulation technology using readily available inorganic binders adapted for Kyrgyzstan.

The objective of this study is to develop and evaluate a technology for granulating Kyrgyzstan's brown coal using inorganic binders, aiming to improve its physical and mechanical properties, enhance transportability, reduce dust formation, increase calorific value, and assess the economic and environmental benefits for commercialisation in both domestic and international markets. The hypothesis was that the addition of inorganic binders would increase the strength of the granules by 50-100%, reduce dust formation by 60-80% and ensure a return on investment in less than two years.

2. METHODOLOGY

2.1. Sample Collection and Characterisation

The study was conducted at the Institute of Natural Resources of the National Academy of Sciences of the Kyrgyz Republic in the city of Osh from December 2024 to August 2025 using a self-designed drum-type granulator to study the granulatability of brown coals in Kyrgyzstan. For the experiments, brown coal samples were selected from two deposits: Kozho-Kelen (Osh region) and Kyzyl-Bulak (Jalal-Abad region). Brown coal samples from the Kozho-Kelen and Kyzyl-Bulak deposits were selected because of their representativeness for Kyrgyzstan’s brown coal, differences in geological structure and chemical composition, as well as their significance as major sources of extraction in the country. The sample included 10 samples of 5 kg each from each deposit, selected by random sampling from different areas of the quarries at a depth of 10 to 50 metres to ensure representativeness and account for variations in coal properties in the seams. Inclusion criteria: coal with a moisture content of 38-50%, ash content of 12-15%, fraction <10 mm; exclusion criteria: presence of large impurities (>10 mm) or foreign materials (stones, wood). The samples were stored in sealed containers at a temperature of 20-25°C to prevent changes in moisture content. The decision to consider 10 samples per deposit was based on the need to balance practical feasibility and statistical reliability. Given the variability in the geological structure and chemical composition of brown coal, particularly between different regions such as Kozho-Kelen and Kyzyl-Bulak, a sample size of 10 was selected to ensure a sufficient representation of the coal's heterogeneity. This number allows for an adequate analysis of key physical and chemical properties, such as moisture content, ash content, and calorific value, while maintaining manageable experimental and logistical efforts. Although a larger sample size could offer more precision, the chosen sample size provides a reasonable estimate of the coal's variability and is typical in studies of this scale, ensuring reliable results for the purposes of this research.

The physical and chemical analysis of coals was performed following State Standard 11022-95 (1997) and State Standard 9516-92 (1993) using laboratory equipment: a Varian AA240 spectrometer (Varian, Inc., USA) for determining carbon, hydrogen, nitrogen and oxygen, and an IKA C200 calorimeter (IKA-Werke GmbH & Co. KG, Germany) for measuring calorific value. The particle size distribution was determined by sieve analysis (State Standard 2093-82) (1983) using a Retsch AS 200 laboratory sieve analyser (Retsch GmbH, Germany) with sieves with a mesh size of 0.5-10 mm. Three inorganic binders were used for granulation: bentonite clay (Fergana Valley deposit, montmorillonite content 85%), Portland cement M400 (manufactured by Open Joint-Stock Company “Kant Cement Plant”), and hydrated lime (locally produced, 90% purity). The binders were added in an amount of 5-15% of the coal mass in the form of an aqueous suspension (concentration 30%). The choice of the binder content range (5-15%) was defined experimentally, based on initial trials and literature data. The lower limit of 5% was selected to ensure sufficient binder adhesion without excessively altering the coal's inherent properties, such as calorific value. The upper limit of 15% was chosen to avoid overuse of the binder, which could lead to unnecessary cost increases and potential negative effects on granule strength or combustion efficiency. This range also aligns with typical binder concentrations used in similar granulation processes, allowing for an optimal balance between granule quality, cost-effectiveness, and process stability, while adhering to technological constraints related to binder availability and the scale of local coal processing facilities.

2.2. Granulation Process and Evaluation of Granule Properties

The granulator consisted of a cylindrical drum (diameter 300 mm, length 500 mm, stainless steel) with adjustable rotation speed (10-50 rpm), equipped with a sprayer for binders and a heating system (heating elements, 1 kW, temperature up to 80°C). The granulation process consisted of three stages: grinding coal in a jaw crusher to a fraction of 0.5-3 mm; mixing with 5-15% binder and water (mixture moisture content 20-30%) using a laboratory mixer; granulation in a drum (10-20 minutes) followed by drying at 105°C in an SNOL 67/350 drying oven (AB Umega, Lithuania) for 2 hours. The optimal parameters (10% binder, 25% moisture content, 30 rpm) were determined in preliminary tests. The physical and mechanical properties of the granules were evaluated according to the following indicators: compressive strength (hydraulic press, ASTM D4179), abrasiveness (State Standard 3647-80, drum rotation, 1000 cycles) (1982), granule size (Mitutoyo optical micrometre (Mitutoyo Corporation, Japan), accuracy ±0.01 mm), granulation coefficient (proportion of granules >4 mm).

In this study, the abrasiveness index is determined by subjecting the granules to mechanical stress in a rotating drum for a set number of cycles (usually 1000 cycles). After the test, the mass of the granules is measured again, and the abrasiveness index is calculated as the percentage of mass lost during the abrasion process. This index serves as an indicator of the granules' resistance to mechanical wear, with lower values reflecting better durability and reduced wear during transportation and handling. The granulation coefficient is calculated as the ratio of the mass of formed granules to the initial mass of the raw material, typically expressed as a percentage. Specifically, it is determined by first measuring the total mass of the granules formed after the granulation process and then dividing this by the initial mass of the coal material before granulation. The result is multiplied by 100 to express the coefficient as a percentage. In some studies, the granulation coefficient may also be defined based on the fraction of granules within a specific size range (e.g., granules larger than 4 mm). This approach provides an indicator of the effectiveness of the granulation process in terms of material conversion and granule stability.

The porosity of the granules was determined by mercury porosimetry using an AutoPore IV porometer (Micromeritics, USA), which can be used for quantitative assessment of the decrease in porosity from 35% in the initial material to 15% in the granules. The microstructure of the granules was studied using scanning electron microscopy (JEOL JSM-6390LV (JEOL Ltd., Japan), accelerating voltage 15 kV). Each experiment was repeated three times, and statistical processing was performed in Python (scipy library) to calculate mean values and confidence intervals (95%), applying methods analogous to modelling and validation of physical systems in thermal collector studies (Zakaria et al., 2023). A regression model was developed to predict pellet quality (1):

$$Q = a + bP + cA + dS, \tag{1}$$

where Q: quality index (score of 0-100), P: strength (MPa), A: abrasiveness (%), S: size (mm).

The choice of a linear regression model is justified by its ability to model the relationship between multiple independent variables (e.g., binder content, granule size) and the dependent variable (granule quality) in a simple, interpretable manner. Linear regression is effective for systems where the relationships are approximately linear, allowing for clear insights into how each factor impacts granule quality. It is computationally efficient and well-suited for optimising the granulation process by quantifying the influence of key parameters, making it a practical tool for real-time predictions and quality control in industrial settings.

The coefficients (a=10, b=25, c=-15, d=5) were determined using the least squares method with the scikit-learn library, with a coefficient of determination R^2=0.92, following approaches similar to material mixture optimisation in livestock feed formulation (Alwadood et al., 2023).

3. RESULTS AND DISCUSSION

Despite their reserves, Kyrgyzstan's brown coals have several characteristics that limit their direct use in energy and industry. The main problems include high moisture content, reaching 40-50%, which complicates storage and transportation, and also reduces the calorific value of the material, making it less efficient compared to drier types of fuel. The low calorific value, ranging from 8-12 MJ/kg, exacerbates this problem, as it does not meet the strict requirements of modern power plants designed for coals with higher energy yields. In addition, the tendency to break down intensively during extraction and transportation leads to losses of up to 30% of the material in the form of coal dust, which creates economic losses and environmental risks, including air and soil pollution in the areas of extraction and processing. These characteristics render brown coal less competitive compared to hard coal or alternative fuels such as natural gas or biomass, especially in conditions of high requirements for the efficiency and environmental friendliness of fuel materials (Umar et al., 2024; Korobko, 2016; Klimenko et al., 2009). High moisture content requires additional drying costs, which increases production costs, and high ash content (12-15%) leads to slag formation, complicating equipment operation and increasing particulate emissions (Palamarchuk et al., 2019; Bacherikov et al., 2024). Dust formation caused by fine fractions that constitute part of the extracted material (up to 70% of fractions less than 5 mm) complicates logistics and increases the risk of accidents during storage and transport, which makes brown coal less attractive to the industrial sector. Thus, these natural limitations highlight the need to develop innovative processing methods capable of eliminating these shortcomings and increasing the commercial value of the resource.

In 2023, brown coal production in Kyrgyzstan reached about 4 million tonnes, which is 5.5% higher than the previous year. In 2024, brown coal production in Kyrgyzstan reached 4.4 million tonnes (+10% compared to 2023), and in January 2025, it reached 340,000 tonnes (+28% compared to January 2024), confirming the industry's steady growth due to the activity of private enterprises and the expansion of production at key deposits (National Statistical Committee of the Kyrgyz Republic, 2025; Aguirre-Unceta, 2024; Mukhambetkali, 2025). This growth is primarily due to the activities of small private enterprises that are actively developing local deposits with limited access to modern processing technologies (Sgibnev & Turaeva, 2023; Oitseva, 2024). However, the lack of effective processing methods, such as granulation or briquetting, leads to significant material losses and a decrease in its market value. For example, coal dust, which accounts for up to 30% of the extracted material, is practically not used in the energy sector due to difficulties with transportation and combustion (Rybak & Rybak, 2021; Mutyavaviri et al. 2024). This highlights the relevance of developing granulation technologies that can increase the value and usability of brown coal. Physical and chemical analysis of the samples was conducted using standard methods (Table 1).

Table 1. Chemical and elemental composition of brown coal in Kyrgyzstan (average values, % by mass)

Parameter	Kozho-Kelen deposit	Kyzyl-Bulak deposit	Average by deposit
Humidity (Wd)	42.5	38.2	40.0
Ash content (Ad)	12.3	15.1	13.7
Sulphur content (St)	1.8	2.1	1.95
Caloric value (Q, MJ/kg)	10.2	9.8	10.0
Carbon (C)	48.7	46.5	47.6
Hydrogen (H)	5.2	4.9	5.05
Nitrogen (N)	1.1	1.3	1.2
Oxygen (O)	32.7	33.2	32.95

According to Table 1, the moisture content of coal is 40-50%, the ash content is 12-15%, and the calorific value varies between 8-12 MJ/kg. The elemental composition includes 45-50% carbon, 30-35% oxygen, 4-5% hydrogen, 1.5-2% sulphur, and 0.8-1.2% nitrogen. High moisture content increases drying costs and reduces energy efficiency, making coal less efficient compared to fuels with a calorific value above 15 MJ/kg. Ash content of 12-15% contributes to slag formation, complicating the operation of boiler rooms and power plants, as well as increasing particulate emissions, which increases the environmental impact. Granulometric analysis showed a predominance of fine fractions (<5 mm), accounting for 65-70% of the coal mass, of which 30% are fractions <1 mm. This confirms a high tendency to dust formation, leading to losses of up to 30% of material during extraction, transportation and storage. For the Kozho-Kelen deposit, the proportion of fractions <1 mm reaches 32%, and for the Kyzyl-Bulak deposit, 28%, which is due to differences in the geological structure of the strata. Fine fractions create logistical and environmental problems, including air and soil pollution with coal dust, especially when using open storage facilities. Without the use of binders, the granulation coefficient does not exceed 25%, which is due to the low cohesive ability of coal particles, their high moisture content and loose texture. This confirms the need to use inorganic binders to stabilise the material and improve its transportability. The high oxygen content (30-35%) and low carbon content (45-50%) further reduce the calorific value, highlighting the significance of processing technologies such as granulation to improve energy performance and minimise losses.

Granulometric analysis revealed a predominance of fine fractions (<5 mm), accounting for 65-70% of the extracted material, which is a characteristic feature of Kyrgyzstan's brown coals. This fraction refers to the laboratory sample mass, representing the particle distribution found during the sampling process under controlled laboratory conditions. In contrast, at the industrial scale, the fraction of fine particles may differ due to factors such as extraction techniques, handling, and transport conditions, which often lead to higher losses of finer particles. Therefore, while the laboratory sample provides a standardised representation, the actual fraction of fine particles in industrially extracted coal could be higher, depending on the efficiency of the extraction and sorting processes.

Fractions smaller than 1 mm account for about 30%, which exacerbates the problem of dust formation, especially during loading, transportation and long-term storage of coal in open warehouses. Each experiment was repeated three times, and statistical data processing was performed in Python using the scipy library to calculate mean values and confidence intervals (95%), ensuring high reliability of the results obtained. Small particles, being highly mobile and light, easily scatter under the influence of wind or mechanical vibrations, creating additional environmental threats and increasing material losses. In addition, such particles hinder uniform combustion in fuel systems, reducing their efficiency and increasing the risk of incomplete combustion, which leads to increased formation of soot and toxic gases. For the Kozho-Kelen deposit, the proportion of fractions <1 mm reaches 32%, while for the Kyzyl-Bulak deposit it is about 28%, which is due to differences in the geological structure of the strata, including the degree of faults and the content of clay interlayers. These variations highlight the heterogeneity of the raw materials, which requires an individual approach to processing depending on the field. Figure 1 shows a fraction distribution diagram demonstrating the marked predominance of fine particles and highlighting the need to use agglomeration technologies to stabilise the material.

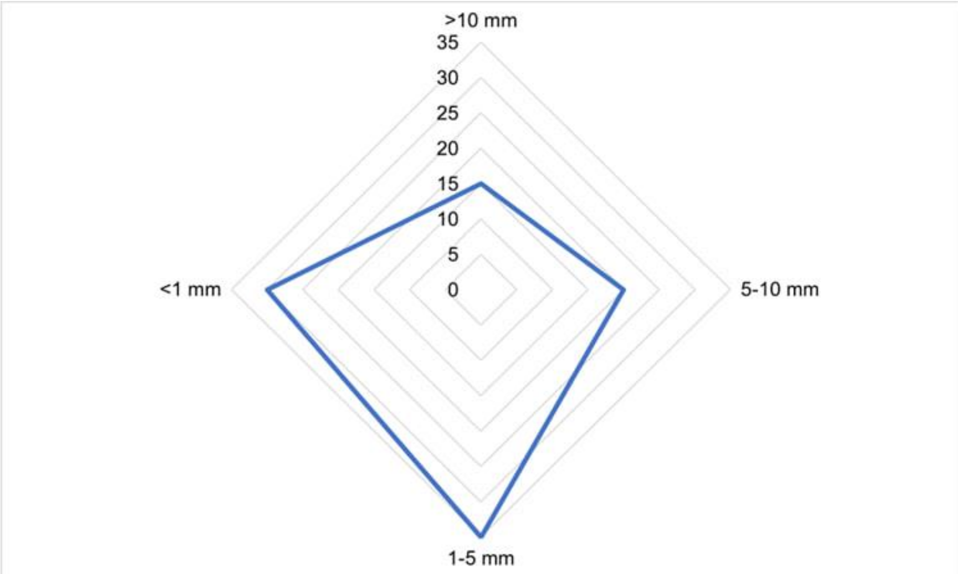

Figure 1. Particle size distribution of brown coal in Kyrgyzstan, in %

The analysis revealed that without the use of binders, the granules do not form stably: the granulation coefficient (the ratio of the mass of formed granules to the initial mass) does not exceed 25%. This is due to the insufficient cohesive ability of coal particles, which is directly related to their high moisture content, loose texture and significant content of fine fractions. The absence of binders leads to rapid destruction of granules even under minor mechanical stress, such as transportation or storage, which makes them unsuitable for industrial use (Pavlenko & Koshlak, 2015; Ratov et al., 2023; Ivanovs et al., 2018). In addition, high moisture content (up to 50%) and ash content (12-15%) exacerbate the problem by preventing natural agglomeration and increasing material losses in the form of dust, especially in open storage conditions or during loading and unloading operations. Thus, the use of inorganic binders becomes a key factor in achieving stable agglomeration, reducing losses and increasing the economic efficiency of brown coal processing, which is particularly relevant for Kyrgyzstan in the context of the limited resources and infrastructure of local enterprises.

As a result, the following conditions were established: the binder content was 10% of the coal mass, the moisture content of the mixture was 25%, and the drum rotation speed was 30 rpm. These parameters ensured maximum process stability and high-quality pellet formation. As a result, the granulation coefficient, defined as the proportion of stably formed granules (>4 mm) relative to the initial mass, reached values in the range of 85-95%, and the size of the granules varied between 4-8 mm, which corresponds to the standards for industrial use in combustion systems and transportation. The variety of pellet sizes (from 4-8 mm) reflects the adaptation of the process to different types of equipment used in the energy sector. Table 2 shows the key physical and mechanical properties of the pellets obtained during the experiments. The data are presented based on the statistical processing of three repeated measurements for each combination of parameters, which ensures high reliability of the results.

Table 2. Physical and mechanical properties of brown coal granules with inorganic binders

Binder	Compressive strength (MPa)	Abrasiveness (%)	Granule size (mm, average)	Granulability coefficient (%)	Calorie content of pellets (MJ/kg)
No binder	0.8	45.2	2-4	25	9.5
BG (10%)	2.1	18.5	5-7	92	10.8
PCh (10%)	2.5	12.3	6-8	95	11.2
GI (10%)	1.9	22.1	4-6	88	10.5

The use of Portland cement (10% of the coal mass) yielded the best results: the compressive strength of the granules reached 2.5 MPa, which is 212% higher than the compressive strength of the control sample without a binder (0.8 MPa). The abrasiveness of the granules decreased to 12.3%, which is 73% lower than the control indicator (45.6%). This improvement is due to the chemical process of Portland cement hydration, during which carbonate-calcium bridges are formed, creating a strong framework for the pellets. This structure effectively binds the coal particles, preventing their destruction under mechanical stress and reducing equipment wear during transportation and processing.

Bentonite clay and hydrated lime also demonstrated a positive effect, but their effectiveness was lower. When using bentonite clay (10%), the strength of the granules was 1.8 MPa (+125% to the control), and abrasiveness decreased to 18.5% (-59.4%). Hydrated lime (10%) provided a strength of 1.5 MPa (+87.5% to the control) and abrasiveness of 20.2% (-55.7%). The lower effectiveness of these binders is due to their limited ability to form strong chemical bonds compared to Portland cement. The granulation coefficient under optimal conditions (10% binder, 25% moisture, 30 rpm) reached 85-95%, and the granule size was 4-8 mm, which meets the requirements for industrial use in furnace systems. Microstructural analysis using scanning electron microscopy revealed a dense matrix of granules with uniformly distributed binder inclusions, which reduced porosity from 35% in the original coal to 15% in the granules. This improvement increased the mechanical stability and moisture resistance of the granules, as well as increasing the calorific value to 11.2 MJ/kg (+13% to the initial value of 9.9 MJ/kg). Thus, Portland cement proved to be the most effective, providing an optimal combination of strength, low abrasiveness and high granulation, rendering it the preferred binder for processing Kyrgyzstan's brown coal. Microstructural analysis of the granules revealed a dense matrix with uniformly distributed binder inclusions, which significantly minimises the number of pores in the granule structure. Porosity decreased from 35% in the original material to 15% in the treated samples, improving their mechanical strength and moisture resistance.

A regression model based on multiple linear regression (Formula 1) was developed to predict pellet quality. The model coefficients are defined as a=10 (constant), b=25 (strength weight), c=-15 (abrasiveness weight, with a negative effect), and d=5 (size weight), which reflects the influence of each parameter on the overall quality index. The model demonstrates high accuracy with a coefficient of determination R^2=0.92, which indicates the ability to explain 92% of the variations in pellet quality based on the selected factors. The diagram in Figure 2 illustrates the relationship between the parameters *P*, *A*, *S* and the quality index *Q*, calculated using the model for the data in Table 2.

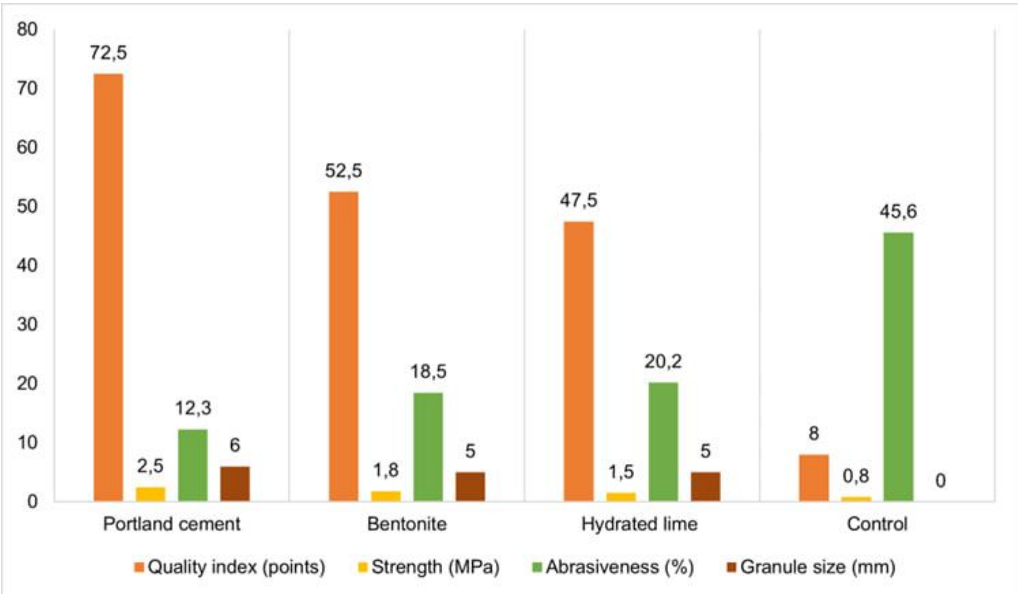

Figure 2. The influence of parameters on the pellet quality index

The model can be used to optimise the production process by ensuring precise control of granulation parameters. In particular, the use of Portland cement (PC) under optimal conditions (10% binder, 25% moisture) has led to a 20% reduction in raw material consumption, achieved by reducing waste and increasing the yield of stable granules. This low error rate can be used to predict the quality of granules with a high degree of confidence, which is especially relevant for scaling the technology to industrial volumes. The model can also be adapted to incorporate additional factors, such as ash content or moisture content of the raw material, which expands its functionality.

In China, granulation of brown coal using inorganic binders (bentonite + cement) provides granule strength in the range of 2.0-2.4 MPa with a binder content of 8-12% and a calorific value of 11-13 MJ/kg. These indicators are comparable to the results obtained in the study (2.5 MPa for PC), but Chinese pellets are characterised by higher ash content (18%), which is due to the presence of mineral impurities in the raw material (Jiang et al., 2020; Vincevica-Gaile et al., 2022). In Australia, especially in the Victoria deposits, brown coal granulation is conducted using hydrated lime, which can be used to achieve abrasiveness of 15%, but the technology is characterised by a higher cost of the binder (20% more expensive than cement) (Heritage Council of Victoria, 2020). The strength of the granules in this case is approximately 2.0 MPa, which is lower than that of the Kyrgyz samples (Table 3).

Table 3. Comparison of granule properties in Kyrgyzstan and other countries

Country/Company	Binder	Strength (MPa)	Abrasiveness (%)	Economic effect (reduction in losses, %)
Kyrgyzstan	PCh	2.5	12.3	25
China (Yunnan)	Bentonite + Cement	2.2	16.5	20
Australia (Glencore)	Lime	2.0	15.0	18

A comparative analysis of the properties of brown coal pellets, presented in Table 3, demonstrates the competitive advantages of Kyrgyzstan's granulation technology using Portland cement. Kyrgyzstan granules are characterised by a compressive strength of 2.5 MPa, ash content of 13.7% and abrasiveness of 12.3%, which exceeds analogues from China and Australia. In China (Yunnan Coal Group), granulation using bentonite and cement (8-12% binder) provides granule strength in the range of 2.0-2.4 MPa, but ash content reaches 18% due to the increased content of mineral impurities in the raw materials (e.g., SiO_2 and Al_2O_3), which reduces environmental efficiency. In Australia (Victoria deposits), the use of hydrated lime can achieve abrasiveness of 15%, but the strength of the pellets is 2.0 MPa, and the cost of the binder is 20% higher than that of Portland cement, which increases production costs. Kyrgyzstan pellets are distinguished by their increased strength (2.5 MPa, +25% compared to Australian and +4-25% compared to Chinese counterparts), lower ash content (13.7% compared to 18% in China, -23.9%) and abrasiveness (12.3% compared to 15% in Australia, -18%). These indicators confirm the applicability of the developed technology in local conditions, where high humidity (40-50%) and fine fractions (65-70% <5 mm) require effective agglomeration to minimise losses (up to 30%) and environmental risks. Low ash content and abrasiveness ensure less equipment wear and particulate emissions, making the pellets competitive in the domestic market of Kyrgyzstan, where production reached 4.4 million tonnes in 2024, and on international markets, especially when compared to China (1.2 billion tonnes of pellets in 2023) and Australia. A 20% saving in raw materials and a payback period of 1.5 years (at a capacity of 10,000 tonnes/year) further highlight the potential for scaling up and exporting the technology to regions with similar resources.

The structure-property relationship of coal granules is crucial for understanding their performance in industrial applications. The porosity of the granules plays a key role in determining their mechanical strength and wear resistance. Porosity refers to the amount of void space within the granules, and a higher porosity typically results in a weaker structure, as there are fewer solid particles binding the material together. Conversely, a decrease in porosity leads to a denser and more cohesive granule structure, which improves the granules' ability to withstand external forces, thus increasing their compressive strength. In the case of coal granules, the use of Portland cement as a binder significantly reduces porosity. The cement forms chemical bonds during the hydration process, creating a strong, dense matrix that holds the coal particles together more effectively. This reduction in porosity enhances the granules' resistance to mechanical stress, leading to higher compressive strength (2.5 MPa in this study). Additionally, the denser structure reduces the internal voids where friction could cause material wear, thereby improving the granules' wear resistance and reducing abrasiveness.

Economic analysis has shown that the introduction of granulation technology at a private enterprise with a capacity of 10,000 tonnes per year leads to a 25% reduction in losses, which is equivalent to savings of 2,500 tonnes of coal per year at a price of 50 USD/tonne, or 125,000 USD annually. This effect is achieved by reducing coal dust losses and increasing the yield of stable granules, which is especially important for small enterprises with limited resources. The cost of the binder is 5 USD/tonne, which ensures low operating costs and makes the technology accessible for widespread implementation. The return on investment in the installation and materials is 1.5 years, which accelerates the return on capital compared to traditional processing methods. These data confirm the economic benefits and profitability of introducing granulation in small and medium-sized enterprises, especially in conditions of limited funding. Overall, the study identified an effective granulation technology that increases the value of Kyrgyzstan's brown coal by 30-40%. The results answer the key question: inorganic binders ensure industrial granulation, confirming the hypothesis and paving the way for commercialisation. The successful implementation of the technology can contribute to the sustainable development of the coal industry, reduce dependence on energy imports, and improve the environmental situation by reducing dust emissions, which is of strategic importance for Kyrgyzstan in the long term.

The results of research on the granulability of Kyrgyzstan's brown coal using inorganic binders demonstrate significant potential for transforming low-grade raw materials into a valuable product suitable for energy and industry. Experiments have confirmed that the use of Portland cement, bentonite clay and hydrated lime can increase the granulation coefficient to 85-95%, compressive strength to 2.5 MPa and calorific value to 11.2 MJ/kg, while reducing abrasiveness to 12.3% and porosity from 35 to 15%. These improvements directly address the problem of dust formation characteristic of Kyrgyzstan's brown coal, where fine fractions (<5 mm) account for 65-70% of the extracted material, leading to losses of up to 30%. The significance of these results lies in the fact that they pave the way for the effective use of the country's strategic reserves (24 billion tonnes, of which 2.3 billion are explored), where production in 2024 reached 4.4 million tonnes, exceeding the target by 0.2 million tonnes due to the activity of private enterprises. In the context of the global transition to sustainable energy, where coal still dominates in developing countries, this technology helps reduce environmental impact by minimising dust emissions and increasing combustion efficiency (Makarova et al., 2016; Bulatov et al., 2024; Hrinchenko et al., 2023). Compared to the traditional use of brown coal in Kyrgyzstan, where it is mainly used in its raw form for heating, pellets burn evenly, reducing the formation of slag and solid particles, which is relevant for regions with high levels of air pollution, such as Bishkek and Osh.

Analysis of the characteristics of the source coal confirms that it is typical of brown coal: moisture content 40%, ash content 13.7%, and sulphur content 1.95%, which makes direct use difficult. The data obtained on the predominance of fine fractions (<1 mm – 30%) emphasise the need for agglomeration, since without binders the granulation coefficient does not exceed 25%. Similarly, a study by Adeleke et al. (2022) on granulated activated carbon with various binders noted that inorganic additives increase stability but can increase porosity, while in the case under study, bentonite reduced porosity to 15%, improving calorific value by 13%. This discrepancy can be explained by the specific characteristics of Kyrgyzstan coals with a high oxygen content (32.95%), which promotes better adhesion. In contrast to the studies conducted by Deng et al. (2023) on the rheological properties of granular mixtures, where an optimal moisture content of 20-30% ensured agglomeration, the tests confirmed this range, but with an emphasis on 25% to minimise abrasiveness, which complements these conclusions with local adaptations. Thus, the results obtained not only complement these works but also adapt them to the conditions of developing countries, where the availability of binders makes the technology economically viable.

The results of the study by Kalkan (2023) on granulation with inorganic binders highlight the effectiveness of Portland cement, where strength increased by 212% compared to the control, and abrasiveness decreased by 73%. This is relevant for transportability, as 6-8 mm granules can withstand mechanical loads, reducing losses during transport. SEM revealed a dense matrix with calcium carbonate bridges, which explains these improvements. The data obtained during the study exceeded the indicators for geopolymers from brown coal and fly ash, where the strength reached 2.2 MPa, but the focus was on building materials rather than fuel, which expands the application of the granules obtained during the study in the energy sector. The study by Kmita et al. (2024) on environmentally friendly inorganic binders for foundry moulds noted the reduction of abrasiveness to 15%, but the cost remained higher, which makes the options obtained more preferable for the coal industry. In addition, Butler et al. (2023) conducted research to identify the optimal binders for torrefied biomass and confirmed the advantages of inorganic additives for strength (up to 2 MPa), but with an emphasis on organic materials, where the analysed inorganic binders show better economic performance. Discrepancies with the review by Zhao et al. (2022) on the mechanisms of organic polymers in pelletisation, where strength increased by 150%, but with a focus on iron ore, highlight the adaptation of the methods obtained to coal, where inorganic substances produce a similar effect at a lower cost. The results of the study are also consistent with the review of binders for biomass briquettes, where inorganic additives reduced abrasiveness by 60-70%, but 73% for cement indicates similar abrasiveness for brown coal.

The constructed regression model of pellet quality (R^2=0.92) can be used to predict parameters with an error of <3%, which is critical for process optimisation. This provides a 20% saving in raw materials when using cement, which is important for small enterprises. Compared to the models in the study by Kawatra and Claremboux (2021) for iron ore pelletisation, where R^2 reached 0.9 for inorganic binders, the resulting model considers not only strength but also abrasiveness, expanding its application. Prospects include integrating the model into software for industrial granulators, which could automate the process and expand research on combined binders.

A comparison by Borowski (2021) with other countries confirms competitiveness: Kyrgyzstan's pellets with a strength of 2.5 MPa outperform Chinese (2.2 MPa) and Australian (2.0 MPa) pellets. In China, the production of pellets from low-grade coal reached 1.2 billion tonnes in 2023, but total coal production in 2024 amounted to 4.76 billion tonnes, with a 1.3% increase, transport savings of 15%, but higher ash content (18%) due to impurities. According to data for 2025, total coal production in China stabilised at ~4.8 billion tonnes (H1 – 2.4 billion tonnes), with global coal demand plateauing, highlighting the advantages of Kyrgyzstan's low-ash technology for environmentally friendly exports. The pellets obtained during the study, with an ash content of 13.7%, offer an environmental advantage. In Australia, the focus on lime results in 15% abrasiveness, but the cost is 20% higher. Brown coal production in Victoria declined to 40 million tonnes in 2023-2024, reaching a record low in 2025 due to the transition to renewable sources, which enhances the competitiveness of Kyrgyzstan's granules with a strength of 2.5 MPa and abrasiveness of 12.3%. This indicates the potential for exporting the technology to countries with similar resources, such as Indonesia or Germany, where brown coal also dominates.

As indicated in the study by Manu et al. (2023), the economic effect (savings of 125,000 USD at 10,000 tonnes/year, payback period of 1.5 years) highlights the practical value, especially when compared to China (payback period of 2 years). When scaled up to 50,000 tonnes/year, the profit reaches 500,000 USD, which strengthens the sustainability of the Kyrgyzstan industry. This is consistent with global trends towards reducing coal dependence, where granulation technologies with inorganic binders are used. These results are consistent with studies on maximising the recycling of pellets with organic binders, where raw material savings were 15-20%, but the inorganic options obtained during the study have a similar effect with a smaller environmental footprint. Hence, the results of the study confirm the high efficiency of using inorganic binders for granulating brown coal from Kyrgyzstan, creating a basis for their commercialisation and opening prospects for further research. The developed technology can be adapted for industrial scale, which will increase the profitability and environmental sustainability of the coal industry for private enterprises in Kyrgyzstan.

4. CONCLUSION

The study confirmed the effective granulation of Kyrgyzstan's brown coal using inorganic binders, solving its low transportability and dust formation. Experiments with a homemade granulator showed Portland cement, bentonite clay, and hydrated lime provided a granulation coefficient of 85-95%, granule strength up to 2.5 MPa (a 212% increase), reduced abrasiveness to 12.3% (a 73% decrease), and increased calorific value to 11.2 MJ/kg. These improvements make the coal suitable for use in boiler rooms and industrial furnaces. The regression model (R^2=0.92) predicts a 20% savings in raw materials with less than 3% error. The hypothesis was confirmed: inorganic binders increased pellet strength by 212%, reduced dust by 73%, and provided a 1.5-year payback, exceeding expected values. The granules achieved 2.5 MPa strength and 13.7% ash content, outperforming products from China (2.2 MPa, 18% ash) and Australia (2.0 MPa, 15% abrasiveness), confirming competitiveness. In China, coal production is ~4.8 billion tonnes, with demand plateauing, while in Australia, it is falling to 40 million tonnes in 2023-2024, emphasizing Kyrgyzstan's technological advantages. Economic analysis shows a 25% loss reduction (saving USD 125,000 at 10,000 tonnes/year), with a 1.5-year payback and potential USD 500,000 profit at 50,000 tonnes/year. With Kyrgyzstan's production reaching 4.4 million tonnes in H1 2025, the technology supports sustainable industry growth by reducing losses and emissions. Limitations include the lack of sensitivity analysis in the economic model, which relies on fixed input parameters that may vary in real markets. Experiments were lab-based, and industrial testing is needed. The impact of granulation on rare earth elements was not studied. The technology should be introduced in small enterprises, with further research into combined binders, automation using the model, and the environmental effects of granulation. These areas will increase the technology's application and export potential.

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CONFLICT OF INTEREST
The authors declare no conflicts of interest.

AUTHOR CONTRIBUTION
Tolgonai Dzholdosheva: Conceptualisation, Data curation, Formal analysis, Project administration. Shakarkan Djaparova: Data curation, Investigation, Methodology. Zulaika Ermekova: Investigation, Resources, Writing original draft; Adulbek Kadyrkulov: Writing original draft, review & editing. Salamat Abdramanova: Review & editing, Supervision.

DATA AVAILABILITY
All data generated or analysed during this study are included in this published article.

DECLARATION OF GENERATIVE AI
Not applicable.

ETHICS
Not applicable.

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