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Organo-Mineral Modification of Coal-Biomass Briquettes for Enhanced Performance and Emission Reduction

V.V. Kukartsev *[a], **L.V. Krasovskaya** [b]
a Russian State Agrarian University – Moscow Timiryazev Agricultural Academy, Moscow, Russian Federation.
b Bauman Moscow State Technical University, Moscow, Russian Federation.

Keywords:
Coal-biomass briquettes; Organo-mineral additives; Porosity reduction; Calorific value; Mechanical strength; Emission control; Thermal stability; Bentonite composite.

Highlights:

- *The incorporation of 20% of organo-mineral additives increased the calorific value to 22.2 MJ/kg.*
- *Total porosity decreased by more than 80%, significantly improving material densification.*
- *Emissions of volatile organic compounds were reduced by approximately 50% during combustion.*

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**Corresponding author:*
V.V. Kukartsev
Russian State Agrarian University – Moscow Timiryazev Agricultural Academy, Moscow, Russian Federation.

Abstract: This study investigates the influence of modified organo-mineral additives on the microstructure, calorific value, mechanical strength, and emission characteristics of coal-biomass briquettes. Experimental work demonstrated that incorporating up to 20% of a thermally treated bentonite-polysaccharide composite significantly reduced total porosity from 58.4 to 11.4% and increased density from 910 to 1070 kg/m³. The calorific value increased by approximately 14%, reaching 22.2 MJ/kg. Mechanical strength improved significantly, with maximum compression load increasing from 580 to 1150 N. Emissions of CO and CO_2 during thermal decomposition decreased by up to 45%, while volatile organic compounds were nearly halved compared to reference briquettes. The kinetic analysis revealed that the activation energy of thermal degradation grew from 136 to 181 kJ/mol, indicating enhanced thermal stability. Additionally, the briquettes demonstrated improved resistance to moisture and abrasion, highlighting their potential for safer storage and transportation. Overall, the results validated the effectiveness of combining coal waste, biomass, and functionalized mineral additives to produce solid fuels with predictable performance and reduced environmental impact.

1.INTRODUCTION

In the modern world, energy security, the rational use of natural resources, and climate mitigation are increasingly important issues for national economies and the international community. According to the International Energy Agency, more than 70% of global energy is still produced by burning coal, oil, and natural gas, which annually emits about 33 billion tons of carbon dioxide into the atmosphere. At the same time, growing volumes of coal mining are accompanied by the formation of vast amounts of waste: in the countries of the European Union and Eastern Europe alone, over 250 million tons of coal sludge, fine fractions, and dust accumulate annually, most of which is stored or disposed of with significant environmental risks [1-4]. Biomass remaining after processing wood, crops, and agro-industrial production also forms a significant volume of secondary resources, exceeding 1.5 billion tons per year according to the Food and Agriculture Organization of the United Nations. Despite the potential of these wastes as an alternative energy source, their utilization in many regions is limited by the technological complexity of processing and the lack of effective systems for integrating them into the energy cycle. One of the key areas of the rational use of carbon-containing waste is the production of fuel briquettes, which helps address resource conservation, reduce waste disposal volumes, and ensure energy supply [5,6]. Briquetting of coal sludge and biomass has become widespread in many European and Asian countries, where the capacity for producing solid biofuels exceeds 60 million tons per year. This approach ensures the production of an energy carrier with a calorific value of 18–25 MJ/kg at relatively low cost and with high technological adaptability. However, despite the advantages of briquettes composed of coal and biomass, there are several serious limitations. First, the products exhibit insufficient mechanical strength, high porosity, low moisture resistance, and a tendency to decompose during storage and transportation. The open porosity of traditional compositions often exceeds 50–60%, which greatly increases the risk of dust formation and spontaneous combustion. In addition, the combustion of such briquettes can result in the intensive release of volatile organic compounds and carbon oxides, thereby reducing the environmental benefits relative to conventional coal [7-10]. To improve performance characteristics and reduce emissions of harmful substances during combustion, several approaches have been proposed in practice worldwide. One of them is the addition of synthetic organic binders, such as carboxymethyl cellulose or polyvinyl alcohol. These additives increase the strength of briquettes by 40-60% and partially reduce dust formation. However, their widespread use is constrained by high costs and dependence on petrochemical raw materials, thereby reducing economic feasibility. Another approach is the preliminary heat- or hydrothermal-treatment of coal and biomass components, which partially reduces porosity and increases the calorific value through dehydration and partial carbonization [11,12]. However, such technologies require significant energy consumption and specialized equipment with high productivity. A promising direction is plasma modification of the particle surface, which improves adhesion and reduces volatile emissions during combustion; however, this approach is applicable primarily to large energy clusters and requires complex process lines. Therefore, the listed methods have important advantages, but are not without disadvantages, including high cost, energy consumption, and complexity of integration into existing production. Against this background, the use of organo-mineral-modified additives in fuel briquette composition is becoming increasingly relevant. While starch-only and clay-only binders are widely employed as low-cost and green options, recent studies indicate that each binder family faces trade-offs among mechanical integrity, moisture resistance, and emissions control. Starch binders tend to enhance densification but may compromise water uptake and long-term durability, whereas clay binders improve thermal stability and water resistance. However, they can dilute the energy content and increase the ash content. Systematic evaluation of organo–mineral hybrids that couple a polysaccharide with activated bentonite across a broad loading window (0–20 wt%) remains limited. Here, we explicitly contrast our bentonite–polysaccharide composite with starch-only and clay-only baselines from recent literature to clarify where hybridization yields net performance gains in strength, porosity, VOC/CO_x emissions, and calorific value [13–15]. Organomineral additives are defined as compositions that combine the binding properties of organic polymers or natural biopolymers with the functional properties of finely dispersed mineral components, such as bentonite, zeolite, kaolin, and their activated forms. The use of such additives increases mechanical strength and reduces porosity, thereby significantly affecting thermal-oxidative degradation and altering the emission of volatile components [16-18]. Studies conducted in recent years have shown that the introduction of organo-mineral modifiers at 8-12% of the mixture weight can reduce the total emission of volatile substances by 20-25% and the total porosity of briquettes by 12-15%. In addition, such compositions exhibit pronounced hydrophobic properties and enhance briquette stability during storage under high-humidity conditions. At the same time, organo-mineral additives are often readily available and low-cost, making their use more economically justified than that of synthetic binders. The relevance of this area stems from several factors. First, in the context of the global transition to low-carbon energy and tightening pollutant-emission standards, minimizing emissions from solid-fuel combustion is particularly important. Secondly, the combined use of coal-industry waste and biomass with the addition of mineral modifiers offers opportunities to obtain energy sources with predictable characteristics and reduced environmental risks [19,20]. Thirdly, the technology for producing briquettes with organo-mineral additives does not require fundamental reconstruction of existing lines and can be implemented using standard pressing and drying equipment. According to specialized reviews, the cost of producing such solid biofuel increases by only 5-7% compared to traditional briquettes, while the strength and moisture resistance indicators increase by more than 1.8-2 times. Moreover, the addition of modified mineral components improves the microstructure of the material, reduces the proportion of open pores, and increases the homogeneity of the distribution of the organic binder over the surface of the particles of carbon-containing raw materials. Based on the presented data, it can be stated that the study of the influence of organo-mineral additives on the structure and kinetics of thermal-oxidative processes during the combustion of fuel briquettes is a timely and important task of both applied and fundamental significance. It substantiates the possibility of producing briquettes with improved operational and environmental properties, thereby enabling new approaches to the utilization of coal-industry waste and biomass. The development of such technologies aligns with modern strategies for sustainable development and climate neutrality in industry and contributes to the creation of alternative fuels that can compete with traditional coal in terms of calorific value while reducing environmental impacts [21-23]. The work aimed to conduct an experimental study of the influence of modified organomineral additives on the microstructural characteristics, porosity indices, and the dynamics of the emission of volatile components during the combustion of coal-biomass briquettes. This involves substantiating the potential to enhance their strength and moisture resistance by incorporating functionalized mineral components into the formulation.

2.RESEARCH METHODS

In this study, a comprehensive experimental plan was implemented to investigate the effects of modified organomineral additives on the microstructure, physicochemical characteristics, and volatile emission indicators during the thermal decomposition of coal-biomass briquettes. All stages of the experiments were carried out using modern analytical and technological equipment that ensures accurate reproducibility and the ability to analyze multifactorial dependencies. To prepare the feedstock, a Retsch RS 200 laboratory vibration mill (Fig. 1) was used to disperse particles of coal sludge, sawdust, and organomineral components to an average diameter of no more than 20 µm. The grinding process was carried out for 90 minutes at a vibration frequency of 1500 rpm, thereby achieving a high degree of homogeneity and activating the surface of mineral and organic phases. The organo-mineral additives consisted of heat-treated bentonite and a polysaccharide modifier prepared by chemical functionalization of sodium polygalacturonate. The ratio of mineral and organic components in the additives varied from 60/40 to 80/20 by weight. The 20 wt% upper limit for the additive was adopted a priori because preliminary mixing and drying trials indicated progressively higher paste viscosity and longer dewatering beyond this level. But our data show diminishing returns between 15 and 20 wt% in strength and calorific value relative to the added material and processing costs. Therefore, 0–20 wt% captures the practically relevant range without compromising pressability and drying consistency. To ensure stable distribution of additives over the surface of the carbon-containing raw material, an IKA MHD 2000/20 planetary mixer with a working chamber volume of 10 l, equipped with an automatic temperature control system (Fig. 2), was used. Mixing was performed at 750 rpm for 20 minutes, maintaining a temperature of 35 °C to prevent premature compaction of the components. The process flow summary (textual schematic instead of a new figure) is feedstock drying and size reduction (coal sludge and sawdust to ≤ 20 µm with a Retsch RS 200), preparation of the organo-mineral additive (thermally treated bentonite with chemically functionalized sodium polygalacturonate, 60/40–80/20 by weight). There is dosing at 0, 5, 10, 15, and 20 wt% high-shear mixing at 750 rpm and 35 °C for 20 min, eccentric pressing at 18 t with a 2.5 min dwell into Ø30 × 25–28 mm briquettes. This also includes vacuum drying at 85 °C and 15 mbar to constant mass (≈ 18 h) and characterization via X-ray micro-CT (5 µm voxel), SEM, STA-MS (30–800 °C; 5/15/25 $°C \cdot min^{-1}$), bomb calorimetry (Parr 6400), and uniaxial compression (Instron 3369). There is moisture-resistance aging (30 °C, 85% RH, 21 days), abrasion (Leco LC-100, 10 h, 45 rpm), and ignition-delay tests (tube furnace at 400 °C).

Fig. 1 The Retsch RS 200 Vibrating Mill.

Fig. 2 The Planetary IKA MHD 2000/20 Mixer.

After preparing the initial mixtures, the briquettes were molded on a Carver Model 3850 laboratory eccentric press with a maximum pressing force of 25 tons. Each batch of briquettes included samples with an organo-mineral additive content of 5, 10, and 15% by weight, as well as control samples without additives. The pressing process was carried out at a load of 18 tons, with a pressure hold of 2.5 minutes. The finished briquettes were cylindrical, with a diameter of 30 mm and a height of 25–28 mm. After pressing, the products were dried in a Memmert VO400 vacuum drying cabinet at a residual pressure of 15 mbar and a temperature of 85°C until a constant weight was achieved, which took an average of 18 hours. To assess microstructural characteristics and porosity distribution, a Bruker Skyscan 1174 X-ray microtomography system with a 5 μm resolution was used. Each sample was scanned at 50 kV tube voltage and 800 μA current for 750 ms. The three-dimensional models were reconstructed with the NRecon software package, and the volume fractions of closed and open pores were analyzed using the CTAn and CTVox programs. Scanning electron microscopy was used to confirm the microtomography results using a JEOL JSM-IT200 operating in high-vacuum mode at an accelerating voltage of 20 kV and a probe current of 60 μA. Microphotographs enabled the recording of the distribution patterns of the binder and modified mineral phases on the surfaces of coal and wood particles. Thermal analysis of degradation and volatile emission was carried out using a NETZSCH STA 449 F3 Jupiter simultaneous thermogravimetric and mass spectrometric system, coupled to a QMS 403 D Aëolos mass spectrometer. Samples weighing 30±1 mg were heated from 30 to 800°C in air at heating rates of 5, 15, and 25°C/min. During the experiment, mass curves, thermal effects, and the composition of gas products were recorded in mass-spectral channels with a resolution of up to 0.5 amu. Analysis of the concentrations of CO, CO_2, CH_4, and light hydrocarbons in emissions enabled us to quantify volatile organic compound emissions. The kinetic parameters of decomposition and activation energies were calculated using the Kissinger method and the Flynn-Wall-Ozawa method based on data from three heating modes. The calorific value was measured using a Parr 6400 oxygen bomb calorimeter, in which briquettes containing approximately 1 g of ground sample were burned at an oxygen pressure of 3 MPa. The tests were performed in triplicate for each composition, and the calorific values were recalculated to account for the moisture content of the original material. Mechanical strength tests were conducted on a Universal Instron 3369 with a 5 kN load cell at a loading rate of 3 mm/min. For each briquette type, the maximum failure load and the nature of deformation were recorded. Additionally, moisture resistance tests were conducted in a Binder MKF 115 climatic chamber at 30 °C and 85% relative humidity. The samples were held for 21 days, after which mass gain was measured and the degree of cracking was visually assessed. All experiments enabled the comprehensive characterization of the effects of organo-mineral additives on the complex properties of coal-biomass briquettes, including microstructure, calorific value, moisture resistance, volatile emissions, and strength indicators.

3.RESULTS AND DISCUSSION

During the work, large-scale experimental studies were conducted to establish the patterns of influence of modified organomineral additives on the structure, thermal characteristics, and gas emissions of coal-biomass briquettes. Within the first series of experiments, a set of samples with different formulations and additive contents was prepared. The original coal sludge, dried at 105 °C for 24 hours, had a residual moisture content of approximately 1.8%. Wood sawdust, constituting 40% of the total mass, was crushed to a particle size of no more than 300 μm and then mixed with the coal component. The organomineral additive was a complex of heat-treated bentonite modified with a polysaccharide solution containing 5% sodium polygalacturonate, which was subsequently chemically activated. The components were mixed in an IKA MHD 2000/20 planetary mixer at 750 rpm for 20 minutes at 35°C to ensure a uniform distribution of the binder over the carbon-containing material. Briquettes were formed in a Carver Model 3850 eccentric press at a pressure of 18 t and a holding time of 2.5 min. Five series of samples were prepared for comparison, with additive contents of 0, 5, 10, 15, and 20%. Each briquette weighed 15±0.2 g, was cylindrical in shape with a diameter of 30 mm, and a thickness of about 27 mm. After pressing, the products were vacuum dried at a temperature of 85°C and a residual pressure of 15 mbar to constant weight, which took from 16 to 20 hours depending on the composition. Microtomographic studies were conducted to characterize the morphology and distribution of pores. The Bruker Skyscan 1174 system allowed us to reconstruct the three-dimensional structure of the samples and determine the proportions of open and closed pores. For briquettes without additives, the total porosity averaged 58.4%, and the proportion of open pores was 49.1%. The addition of 10% of the organomineral composition reduced these figures to 23.6 and 18.9%, respectively. With an additive content of 20%, the total porosity decreased to 11.4%, and the open component was only 6.2%. Relative to 15 wt%, however, the incremental gains at 20 wt% are modest across several metrics (e.g., the higher heating value of 22.0→22.2 MJ·kg^{-1}; the peak CO_2 mass release of 128→114 mg·g^{-1}; the compression load of 1080→1150 N), indicating diminishing returns as the matrix approaches a densification plateau. This observation supports our choice of 20 wt% as a practical upper bound balancing performance improvements against processability and cost. The structure's density was further confirmed by the results of scanning electron microscopy on a JEOL JSM-IT200 installation. Micrographs demonstrated the formation of a more uniform binder coating of the particles, as well as a significant reduction in intergranular voids. To quantitatively determine the calorific value, tests were performed in a Parr 6400 calorimeter. The average calorific value of briquettes without additives was 19.4 MJ/kg. The addition of 5% of the organomineral additive increased this indicator to 20.8 MJ/kg. At an additive content of 10%, the calorific value increased to 21.6 MJ/kg, and at 20% it reached a maximum of 22.2 MJ/kg (Table 1). This increase is attributable to the additional energy potential of the binder's organic component and to a denser structure, which enhances combustion.

Table 1 The Influence of Organic-Mineral Additive Content on the Heating Value and Moisture Content of Briquettes.

Additive content, %	Average calorific value, MJ/kg	Standard deviation, MJ/kg	Humidity after drying, %	Average density, kg/m³
0	19.4	±0.3	1.8	910
5	20.8	±0.2	1.6	970
10	21.6	±0.2	1.5	1015
15	22.0	±0.2	1.4	1040
20	22.2	±0.2	1.3	1070

The most important area of the study was the investigation of gas evolution during thermal decomposition. A NETZSCH STA 449 F3 Jupiter thermal analysis system with a QMS 403 D Aëolos mass spectrometer recorded the flows of CO, CO_2, CH_4, and volatile hydrocarbons during sample heating from 30 to 800 °C at rates of 5, 15, and 25 °C/min. For the briquettes without additives, the peak CO evolution was observed at 372 °C (38.2 mg/g), and CO_2 at 389 °C (185 mg/g). With the addition of 10% of the organomineral additive, the maximum concentrations of CO and CO_2 decreased to 27.6 mg/g and 142 mg/g, respectively, indicating more stable thermal-oxidative behavior. At 20% additive content, CO and CO_2 emission peaks were observed at 382 and 394°C, respectively, and mass emission was reduced by 41–46% relative to the control (Table 2). The volume of hydrocarbons emitted also decreased: for briquettes without additives, the total yield of light organic compounds was 12.8 mg/g, whereas with 15% additive, it decreased to 6.3 mg/g.

Table 2 Parameters of Gas Release During Thermal Decomposition of Briquettes with Different Additive Contents.

Additive content, %	Peak CO release, mg/g	Peak CO temperature, °C	Peak CO_2 release, mg/g	Peak CO_2 temperature, °C	Total light hydrocarbon yield, mg/g
0	38.2	372	185	389	12.8
5	32.1	374	161	390	9.7
10	27.6	379	142	392	7.5
15	24.2	381	128	393	6.3
20	22.5	382	114	394	5.8

Kinetic calculations using the Kissinger and Flynn-Wall-Ozawa methods showed that the activation energy of thermal degradation of briquettes increases with increasing the additive content. For control samples, the activation energy was 136 kJ/mol, with an additive of 10%-163 kJ/mol, and it reached 181 kJ/mol with 20%. This indicated a slowdown in decomposition processes due to increased bond strength and a denser matrix structure. The results of compression tests showed a pronounced dependence of mechanical strength on the proportion of the modified component. For the control briquettes, the maximum failure load was 580 N; with a 5% additive, it increased to 740 N, and with 15%, it reached 1080 N. With a 20% additive content, the strength was recorded at 1150 N. Measuring moisture resistance in a Binder MKF 115 climatic chamber at 85% of humidity and 30°C showed that after 21 days, the weight gain for the control samples was 6.2%, while for briquettes with 15% of the additive, it was only 2.4%. Analysis of the microstructure using X-ray microtomography revealed that, for briquettes with a 20% additive, the volume of closed pores increased from 2.6 to 4.2 mm³, whereas the volume of open pores decreased from 320 to 44 mm³, further confirming significant compaction of the material (Table 3).

Table 3 Morphometric Parameters of the Briquette Microstructure Based on Microtomography Data.

Additive content, %	Total porosity, %	Percent open pores, %	Percent closed pores, %	Average pore size, μm	Open pore volume, mm³	Closed pore volume, mm³
0	58.4	49.1	9.3	75	320	2.6
5	33.2	25.4	7.8	52	161	3.1
10	23.6	18.9	4.7	43	92	3.8
15	15.2	9.6	5.6	31	58	4.0
20	11.4	6.2	5.2	27	44	4.2

In comparison with the data of other studies, where the use of lignosulfonates as a binder provided a decrease in porosity by an average of 25-35%, our results demonstrated a more pronounced effect, allowing us to reduce the proportion of open pores by more than 80%. Similarly, calorific values reported in several publications using organic binders reached 21 MJ/kg, whereas the combined use of the organo-mineral composition in this study increased calorific value by up to 22.2 MJ/kg. This indicates the potential for using this approach to create fuel with improved performance properties. Additional test series included an analysis of abrasion resistance. For this, 20 samples of each formulation were subjected to a 10-hour rotation in a Leco LC-100 drum at 45 rpm. According to the results, the control samples lost up to 14.3% of their mass due to abrasion and dust formation, whereas briquettes containing 15% of the additive showed losses of no more than 5.1%. With the 20% organomineral additive content, abrasion was only 3.8%, which reflects a significant increase in resistance to mechanical damage. An important aspect of the study was the study of ignition speed. When using a tubular furnace with programmable heating and temperature control, it was observed that the control briquettes ignited after an average of 78 s after reaching a temperature of 400°C, while samples with 15% of the additive ignited after 96 s. At 20% additive, the ignition time increased to 112 s, indicating delayed oxidation and improved fire safety (Table 4).

Table 4 Dynamics of Ignition and Abrasion of Briquettes.

Additive content, %	**Ignition time at 400 °C, s**	**Abrasion weight loss, %**	**Average maximum compression load, N**	**Weight gain with 85% of humidity, %**
0	78	14.3	580	6.2
5	83	9.2	740	4.3
10	89	6.7	930	3.2
15	96	5.1	1080	2.4
20	112	3.8	1150	2.1

Analysis of the intensity of gas evolution at different stages of heating showed that the main contribution to CO_2 emission was from dehydration and destruction of the organic binder in the temperature range from 320 to 480°C. At the same time, as the proportion of the mineral phase increased, the maximum gas emission shifted by 10–15°C toward higher temperatures. This is due to the formation of more stable interphase bonds and partial sorption of volatile decomposition products on the bentonite surface. A comparative analysis of results from studies using synthetic binders showed that the efficiency of reducing volatile emissions with organo-mineral additives was comparable to or exceeded that of similar methods. Therefore, according to Van der Westhuizen et al., the use of styrene-acrylic polymers reduced volatile compound emissions by 30–40%, whereas in our findings, the reduction was 45–55%, with lower raw material costs and lower energy costs for modification. Based on the results, it was established that the introduction of modified organo-mineral additives significantly improved briquette characteristics. They demonstrated a more than twofold increase in strength, a 3-4 fold decrease in porosity, a decrease in the emission of volatile organic compounds of almost two times, and an increase in calorific value by 15% relative to the original composition. These results indicate the high efficiency of the approach for integrating coal waste, biomass, and activated mineral components to produce a solid fuel with predictable performance properties and minimal environmental impact during combustion.

4.CONCLUSION

Based on the experiments conducted, it can be concluded that the use of modified organo-mineral additives in coal-biomass briquette formulations significantly improves their physical, chemical, and operational properties. The addition of heat-treated bentonite activated by a polysaccharide component significantly reduced overall porosity, particularly the proportion of open pores, which decreased from 49.1% in the control samples to 6.2% at the maximum additive content. This structural compaction was accompanied by an increase in material density, from 910 to 1070 kg/m^3. The calorific value indicators also demonstrated positive dynamics: whereas for briquettes without additives the calorific value averaged 19.4 MJ/kg, with a 20% organo-mineral composition, it increased to 22.2 MJ/kg. This increase, exceeding 14%, was explained by both a denser structure that facilitates efficient combustion and the intrinsic energy contribution of the organic component of the modifier. Mechanical tests confirmed a significant increase in strength. The maximum compressive load increased from 580 N in the original samples to 1150 N at an additive content of 20%, more than twice the initial value. At the same time, abrasion resistance improved significantly: mass loss over 10 hours of drum testing decreased from 14.3% for control briquettes to 3.8% for the samples with 20% of the additive. In addition, changes in moisture resistance characteristics were recorded: at high air humidity, the mass gain over three weeks of storage decreased from 6.2% to 2.1%, indicating a pronounced hydrophobic effect of the composition. Analysis of thermal-oxidative degradation demonstrated a decrease in the intensity of gas evolution. The mass of emitted carbon dioxide decreased from 185 to 114 mg/g, and carbon monoxide decreased from 38.2 to 22.5 mg/g, indicating more stable briquette behavior during heating. The reduction in volatile organic compound emissions was 55% relative to the control samples. The ignition time increased from 78 to 112 s, indicating slower oxidation and improved fire safety. Kinetic analysis confirmed that the activation energy of the decomposition processes increased from 136 to 181 kJ/mol, attributable to increased interfacial interactions and a decrease in the degradation rate of the organic matrix. The results obtained are comparable and, in some respects, exceed those reported in the literature on the use of synthetic binders, such as styrene-acrylic polymers and lignosulfonates. With lower energy production costs and more accessible raw materials, the use of organo-mineral additives led to a more pronounced reduction in porosity and volatile emissions, as well as a significant increase in mechanical strength and calorific value. The comprehensive approach implemented in the study demonstrated that the integration of coal sludge, wood biomass, and activated mineral components allows for the creation of fuel with predictable characteristics that exceed traditional solid biofuel indicators in several key parameters.

Therefore, this technology can be considered an effective means of increasing the environmental and operational efficiency of fuel briquettes without significantly increasing production costs. Compared with lignosulfonate- and PVA-based binders, the bentonite–polysaccharide hybrid used here provides an equal or higher heating value, markedly lower VOC/COx emissions, improved moisture and abrasion resistance, and compatibility with existing briquetting lines. The process flow relies on standard grinding, mixing, pressing, and low-temperature drying equipment commonly used in briquetting lines, thereby facilitating industrial uptake without capital-intensive retrofits. Given the local availability and low unit cost of bentonite and polysaccharides, the additive typically accounts for a minor share of the total cost. In our context, the expected cost increase for hybridized briquettes remains within the ~5–7% envelope discussed in the Introduction, while delivering outsized gains in strength, porosity, and emissions behavior. These characteristics indicate a favorable pathway for scale-up in small- to medium-sized production facilities, with potential for further optimization via local sourcing and waste-derived biopolymers.

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

V.V. Kukartsev: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Writing – original draft, Visualization. L.V. Krasovskaya: Resources, Validation, Supervision, Writing – review & editing, Project administration, Funding acquisition.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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