

Production of Refuse-Derived Fuel Pellets from Wood and Agricultural Waste: Technological Solutions and Economic Efficiency

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Abstract — The study assesses the potential of Russia's wood and agricultural waste for bioenergy. A technology for producing composite refuse-derived fuel (RDF) pellets from this feedstock is proposed, along with an economic evaluation. Optimal blend ratios are identified to ensure the pellets comply with the state standard (GOST) 33103.2-2017 and exhibit high mechanical durability ($\geq 93\%$). Economically viable production is achievable when lignin is sourced as a zero-cost by-product and raw material prices remain below specific thresholds. Pellets with higher lignin content demonstrate the best economic performance. The results highlight that feedstock composition and preparation are critical factors influencing pellet quality, energy value, and cost-effectiveness, which are essential for advancing sustainable bioenergy in Russia.

Index Terms — Bioenergy, composite fuel, economic efficiency, energy potential, mechanical durability, RDF pellets, torrefaction, wood and agricultural waste.

I. INTRODUCTION

At present, the depletion of natural resources represents one of the most serious threats facing society. Rapid population growth intensifies demand for water, energy, and food, exacerbating this challenge and stimulating the search for sustainable solutions. Biomass utilization

emerges as a promising avenue for mitigating both the energy crisis and environmental degradation [1]. As a renewable feedstock, biomass possesses significant potential, low environmental impact, and a high degree of versatility in application. At the international level, biomass is recognized as a carbon-neutral energy source and a renewable fuel [2]. Rather than being regarded merely as waste or unused material, biomass should be valued as a resource capable of yielding various products and energy with minimal environmental footprint. A circular economy approach enables maximization of resource efficiency while promoting the sustainable use of biomass [3]. The feedstock base for biomass-derived fuels consists primarily of waste streams from the forestry and agricultural sectors [4]. These wastes are actively employed in the production of pelletized fuel, which is subsequently utilized for heating and cooking in Scandinavian countries, Canada, Russia, and many other regions worldwide [5].

Pelletization of such feedstock is a complex process accompanied by several technical challenges related both to inherent biomass properties and to granulation technology. Biomass materials – such as sawdust, straw, and husks, – typically exhibit low bulk density and heterogeneous moisture content, necessitating preliminary preparation and drying [6]. Furthermore, biomass particles demonstrate low natural adhesion; insufficient heating during pelletization may therefore lead to pellet disintegration. When processing herbaceous biomass (e.g., straw, hay), material adhesion to die walls can occur, hindering continuous operation. To overcome these issues, various binders are commonly employed [7–9]. Pelletization is an energy-intensive process, consuming approximately 50–100 kWh per tonne of product [10].

Notably, wood and agricultural residues impose significant environmental burdens; yet simultaneously, they constitute a largely underutilized energy resource that

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can be valorized via refuse-derived fuel (RDF) technologies. RDF pellets have found widespread application in co-firing with coal at large-scale thermal power plants [11]. The quality of such pellets is governed by the technical standards EN ISO 17225 – Solid Biofuels. RDF pellets produced from agricultural residues (e.g., straw, miscanthus, rice husk, olive pomace, etc.) must meet specific requirements, including mechanical durability (>90%), ash content (<8%), and limited chlorine and sulfur levels to prevent slagging and corrosion during combustion.

Despite the progress achieved, the formulations of RDF pellets from wood and agricultural waste remain insufficiently optimized, which limits their integration into sustainable energy systems [12]. This is attributed to the need for various preparatory procedures for different types of waste and the use of different binders, such as torrefaction [13]. The use of RDF is expanding in Russia and globally, yet it is still constrained by limitations in the waste-to-energy sector.

The main challenges in biomass pelleting are associated with feedstock characteristics and equipment settings. It is important to note that optimizing blends with local biomass is crucial and highly relevant for Russia, which faces significant obstacles – limited resource availability and economic feasibility.

In this context, this paper implements a regionally-oriented approach with three interconnected objectives: 1) assessment of the extractable energy potential of wood and agricultural waste for bioenergy needs; 2) development of a technology for producing composite RDF pellets from locally available waste with an optimal ratio ensuring compliance with quality standards; 3) a techno-economic

assessment aimed at determining the maximum acceptable feedstock prices and waste integration scenarios under which RDF pellet production becomes commercially viable in current Russian market conditions.

II. ASSESSMENT OF THE POTENTIAL OF WOOD AND AGRICULTURAL WASTE FOR BIOENERGY APPLICATIONS

According to data from Rospotrebnadzor (the Federal Service for Surveillance on Consumer Rights Protection and Human Wellbeing), in 2022, Russia generated 5.94 million tonnes of wood waste and 2.97 million tonnes of crop production residues [14].

Figure 1a illustrates the regional distribution of wood waste across federal districts in Russia for 2022. These values were estimated based on national statistics on total waste from the forest processing industry (FPI) [14] combined with regional data on timber harvesting volumes [15, 16]. The largest volumes of wood waste originated in the most forested federal districts—namely, the Siberian Federal District (SFD), accounting for 30.3% of the national total, and the Northwestern Federal District (NWFD), contributing 26.3%. In contrast, wood waste generation in the Southern (StFD) and North Caucasian (NCFD) Federal Districts was negligible (<1% each).

Crop production is a sector characterized by a high waste-to-product ratio: the yield of the primary (marketable) product typically constitutes no more than 30% of the initial biomass input. Figure 1b presents the regional distribution of crop residues in Russia for 2022, calculated using national data on agricultural waste volumes [14] and regional data on cultivated areas for major crops in 2022 [17]. The largest quantities of crop

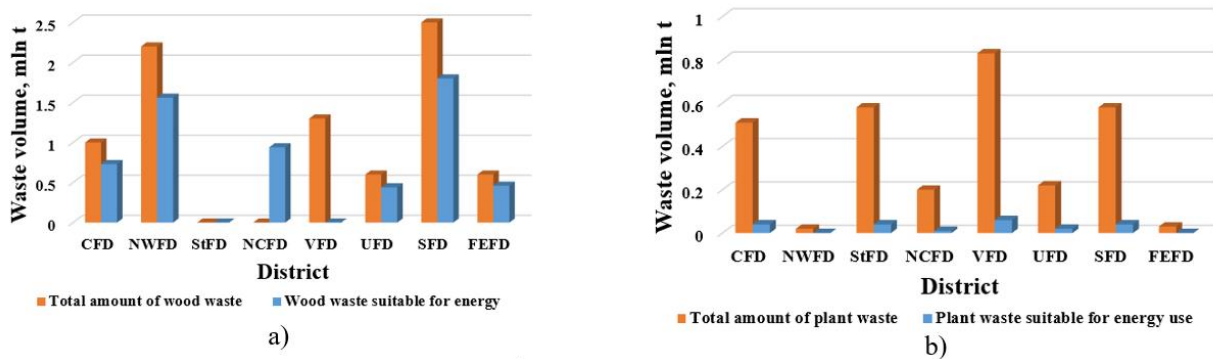


Fig. 1. Volumes of wood waste (a) and crop residues (b) in Russia in 2022, by Federal District.

TABLE 1. Energy Potential of Wood Waste and Crop Residues

Federal District	Fuel consumption, Mtoe	Energy potential, Mtoe		Potential share of total fuel demand, %		
		Wood	Ag-waste	Wood	Ag-waste	Total
CFD	99.60	0.26	0.01	0.26	0.01	0.28
NWFD	63.36	0.56	0.00	0.89	0.00	0.89
StFD	27.18	0.00	0.01	0.02	0.05	0.06
NCFD	10.86	0.00	0.00	0.01	0.03	0.04
VFD	99.29	0.34	0.02	0.34	0.02	0.36
UFD	121.45	0.16	0.01	0.13	0.01	0.14
SFD	71.82	0.65	0.01	0.90	0.02	0.92
FEFD	36.72	0.16	0.00	0.45	0.00	0.45
RF	530.28	2.14	0.07	0.40	0.01	0.42

residues in 2022 were generated in the Volga Federal District (VFD), representing 28.6% of the national total, followed by the Siberian (SFD), Central (CFD), and Southern Federal Districts – each contributing approximately 19.1%. Notably, residues from cereal and grain-legume crops – which are among the most promising feedstocks for bioenergy applications accounted for 55–70% of total crop residues in 2022 [14].

Depending on the specific economic activities prevailing in different regions of Russia, the ratios of both generated and utilized waste vary significantly. For instance, the Southern Federal District (StFD) is characterized by a well-developed agricultural sector, utilizing on average 64% of Russian agricultural waste, whereas the Siberian (SFD) and Northwestern (NWFD) Federal Districts are primarily oriented towards forestry. According to official statistics, these regions utilized 82.5% of wood waste in 2022 [18].

Despite the substantial total volume of wood and crop residues – 11.2 million tonnes – their combined energy potential remains relatively low. Due to economic and technological constraints, only up to 6 million tonnes are currently considered feasible for energy recovery. Consequently, in 2022 the energy potential of wood and crop residues amounted to just 0.42% of Russia's total fuel consumption [19].

It should be noted that the highest energy potential from these two waste streams is concentrated in the Siberian Federal District (SFD: 0.66 million tonnes of oil equivalent, Mtoe) and the Northwestern Federal District (NWFD: 0.56 Mtoe), owing to their dominant share of wood waste generation. The Volga Federal District (VFD) ranks third (0.36 Mtoe), with a less developed forest processing industry but a more advanced agro-industrial complex (Table 1).

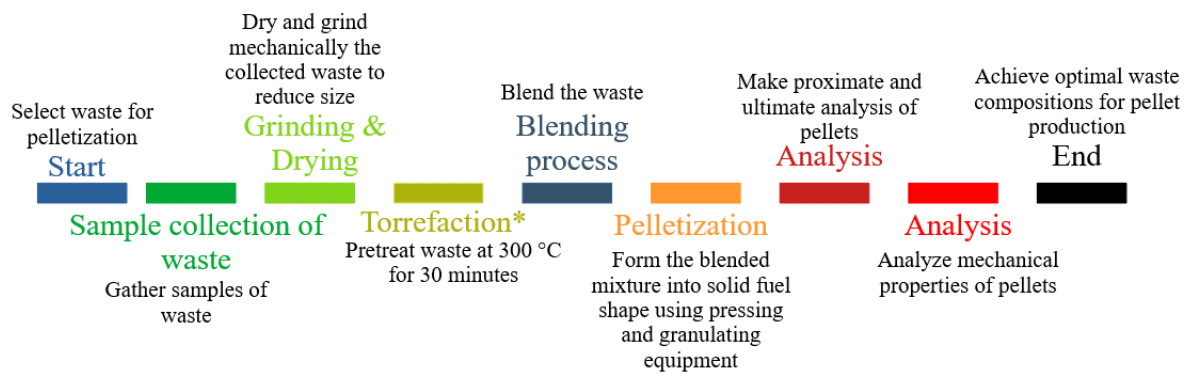


Fig. 2. The procedure to produce RDF.

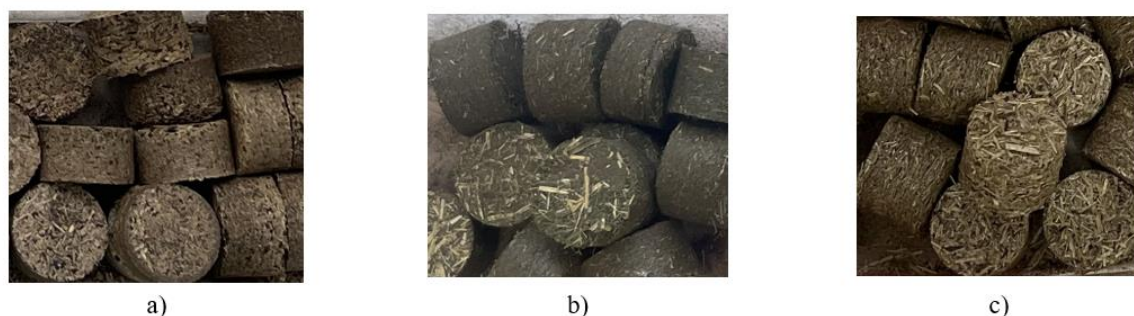


Fig. 3. The appearance of RDF pellets: a) pine sawdust-to-lignin ratio of 58% / 42%; b) straw-to-mixed-grasses ratio of 25% / 75%; c) torrefied sunflower husk-to-straw ratio of 15% / 85%.

III. PELLETIZATION OF WOOD AND AGRICULTURAL WASTE

Despite the relatively modest energy potential of wood and crop waste, the pellet production market demonstrates a stable growth trend. Among the principal wood-derived feedstocks are by-products of the forest industry – primarily sawdust and lignin, the latter being a residue from hydrolysis and pulp-and-paper production. Promising agricultural waste in the Russian context include sunflower husk, straw (both individually and in combination with mixed grasses), and mixed grasses commonly harvested as livestock fodder.

The experimental study focused on producing composite pellets from the selected wood and agricultural residues: pine sawdust, lignin (supplied as waste from the Baikal Pulp and Paper Mill), sunflower husk, straw, and mixed grasses. These raw materials underwent preliminary preparation – including drying, size reduction, and conditioning – to enable granulation into dense, solid pellets suitable for subsequent physicochemical characterization.

Figure 2 illustrates the step-by-step process for RDF pellet production, encompassing raw material collection, size reduction, drying, torrefaction (* – if necessary for a specific material), granulation (pelletizing), proximate and ultimate analysis, and analysis of mechanical properties, and finally the determination of optimal waste ratios in composite RDF pellets.

It should be noted that feedstock pretreatment prior to pelletization varies depending on the waste type. Straw comprising dried stems and leaves of cereal crops remaining after threshing can reach lengths of 60 cm to 1.5 m, with considerable variation in stalk thickness; therefore, it was milled, and the 3–6 mm fraction was selected for further study. Mixed grasses were freshly cut and exhibited high initial moisture content (~60%); they

were air-dried to an equilibrium moisture level of ~6%. Pine sawdust was dried in a ventilated room to air-dry condition and sieved, after which the 3–6 mm fraction was retained. Lignin from the Baikalsk Pulp-and-Paper Mill (BPPM) is a plastic, clay-like, finely dispersed material with moisture content up to 85%; samples were oven-dried at 105 °C to near-absolute dryness (3% moisture). Sunflower husk, the outer shell of sunflower seeds (6–8 mm long, 4–5 mm wide), is difficult to mill in its raw state, and unprocessed husk yields mechanically unstable pellets. Hence, sunflower husk was first torrefied in a screw reactor at 300 °C for 30 minutes and subsequently ground using a high-speed laboratory mill.

Following pretreatment, composite mixtures were prepared in varying proportions for RDF pellet production, targeting combinations with high utilization potential:

- Pine sawdust – lignin: 100% / 0%, 95% / 5%, 88% / 12%, 77% / 23%, 58% / 42%, 40% / 60%;
- Torrefied sunflower husk – straw: 10% / 90%, 15% / 85%, 25% / 75%, 100% / 0%;
- Straw – mixed grasses: 100% / 0%, 75% / 25%, 70% / 30%, 50% / 50%, 0% / 100%.

Pelletization was performed using a standard hydraulic press operating at 5 tonnes of force (scale-up to screw or flat-die pelletizers is planned for future work). The resulting pellets had a diameter of 20.5 mm and heights ranging from 12.5 to 14.5 mm. Figure 3 shows the

TABLE 2. Ultimate Analysis of Waste

Name	C, %	H, %	O, %	S, %
Pine sawdust	46.6	6.3	47.1	–
Lignin	54.2	4.5	39.7	0.12
Straw	46.5	5.4	48.1	–
Mixed grasses	43.3	6.1	50.2	0.37
Sunflower husks	39.7	5.8	53.4	1.10
Sunflower husks (torrefied)	47.5	4.7	47.2	0.63

TABLE 3. Proximate Analysis and Analysis of Mechanical Properties of Pellets

No.	Composition of RDF pellets	Volatile matter, %	Ash content, %	Low calorific value, MJ/kg	Bulk density, g/ml	Mechanical durability, %
Pine sawdust (%) / lignin (%)						
1	100/0	87±0.96	1.52±0.03	17.91±0.45	0.38±0.02	96.1±0.72
2	95/5	80±0.88	3.20±0.06	18.28±0.46	0.43±0.02	96.3±0.72
3	88/12	78±0.86	4.00±0.08	18.17±0.45	0.46±0.02	95.7±0.72
4	77/23	72±0.79	7.00±0.13	17.56±0.44	0.50±0.02	92.3±0.69
5	58/42	66±0.73	8.50±0.16	17.08±0.43	0.45±0.02	87.3±0.65
6	40/60	63±0.69	10.50±0.20	16.00±0.40	0.53±0.02	79.3±0.59
Torrefied sunflower husks (%) / straw (%)						
7	100/0	63±0.69	6.97±0.13	22.07±0.55	0.57±0.03	30.2±0.23
8	25/75	73±0.80	5.65±0.11	19.20±0.48	0.42±0.02	91.7±0.69
9	15/85	75±0.83	4.65±0.09	17.18±0.43	0.44±0.02	93.2±0.70
10	10/90	77±0.85	5.01±0.10	16.88±0.42	0.40±0.02	95.7±0.72
Straw (%) / mixed grasses (%)						
11	100/0	80±0.88	5.44±0.10	16.85±0.42	0.33±0.02	95.9±0.72
12	50/50	80±0.88	7.80±0.15	16.89±0.42	0.55±0.03	93.0±0.70
13	30/70	79±0.87	14.70±0.28	15.79±0.39	0.59±0.03	91.6±0.69
14	25/75	75±0.83	17.60±0.33	15.30±0.38	0.54±0.03	90.3±0.68
15	0/100	73±0.80	13.20±0.25	16.85±0.42	0.49±0.02	87.1±0.65

appearance of the produced RDF pellets.

The proximate analysis, ultimate analysis, and analysis of mechanical properties of the produced composite RDF pellets were performed using the resources of the High-Temperature Circuit Multi-Access Research Center (MESI SB RAS): a macro-thermogravimetric analyzer (TGA 801), an AC 500 calorimeter, and elemental analyzers for carbon (C), hydrogen (H), and sulfur (S). Bulk density was measured in accordance with State Standard (GOST) 54191–2010, and mechanical durability was assessed following GOST R 55110–2012. The moisture content of all pellet samples was maintained within 3–5%. Table 2 presents the ultimate analysis of the main RDF pellet components, normalized to a dry, ash-free basis.

Table 3 presents the proximate analysis and analysis of mechanical properties of 15 different composite formulations of the produced RDF pellets.

Analysis of Table 3 reveals several trends.

For RDF pellets produced from pine sawdust and lignin, an increase in lignin content leads to a systematic decrease in volatile matter yield (from 87% to 63%) and lower heating value (LHV) (from 18 to 16 MJ/kg), while ash content and bulk density rise. Mechanical durability declines from 96.1% to 79.3% as the lignin proportion

increases. Therefore, the optimal lignin content should not exceed 23%, since higher shares substantially impair pellet integrity.

Pellets produced from torrefied sunflower husks and straw show an increase in volatile matter yield as the straw content increases, accompanied by a reduction in heating value and ash content. Notably, pellets composed solely of sunflower husk exhibit the lowest mechanical durability among all tested formulations – only 30.2%. However, incorporation of straw markedly improves durability, reaching 95.7% at 90% straw content. Consequently, the minimum recommended sunflower husk content is no more than 10% to ensure adequate binding and structural stability while preserving the benefits of husk inclusion (e.g., ash composition modulation, waste valorization).

In the case of straw-mixed grass blends, an increase in the proportion of mixed grasses reduces volatile matter yield and raises ash content, whereas the LHV remains relatively constant (~15–16 MJ/kg) across all blend ratios. Mechanical durability shows a linear decline with rising grass content. Hence, to ensure acceptable pellet quality, the straw content should be at least 50%, as this composition delivers the best overall balance of mechanical strength and combustion properties.

Only 7 RDF pellet options – highlighted in black in Table 3 – achieve mechanical durability $\geq 93\%$, thereby meeting the requirements of GOST 33103.2-2017 (Solid biofuels – Technical specifications and fuel classes – Part 2: Classification of wood pellets) and qualifying for use as solid biofuel.

IV. ECONOMIC EFFICIENCY OF PELLET PRODUCTION

Since pellets, as a fuel, are typically not consumed at the production site but rather transported over long distances [20–22], mechanical durability was selected as the primary criterion for evaluating economic feasibility: high durability ensures minimal degradation (dust formation, breakage) during handling, storage, and transport, thus preserving fuel quality and calorific value. Within this study, RDF pellets exhibiting mechanical durability above 93% were considered promising for commercial production.

Additionally, pellets composed of 23% lignin and 77% sawdust, though marginally below the 93% threshold (92.3% durability), were also considered in the economic assessment. Their inclusion is justified by the significant advantage of enabling industrial-scale lignin valorization, thereby transforming a costly waste stream (e.g., from pulp

mills) into a valuable co-feedstock.

Accordingly, the economic assessment presented herein covers eight pellet formulations identified in Table 3 as technically viable candidates (including the 23% lignin option). This analysis considers raw material costs, processing requirements, and market conditions to determine production feasibility in the Russian economic landscape.

A. Methods and Input Data for the Economic Assessment

To evaluate the economic viability of producing fuel pellets from wood and agro-industrial waste, this study employs three standard investment appraisal indicators: Net Present Value (NPV), Discounted Payback Period (DPP), and Internal Rate of Return (IRR) [23].

The Net Present Value (NPV) is calculated using equation

$$NPV = \sum_{t=0}^n \frac{NCF_t}{(1+r)^t} - \sum_{t=0}^n I_t, \quad (1)$$

where NCF_t is the net effective cash flow in year t , million RUB; r is the discount rate, I_t is the investment expenditure in year t , million RUB/year; n is the project lifetime, years.

Based on (1), the Discounted Payback Period (DPP) is

TABLE 4. Input Economic Parameters Used in the Calculations

Parameter	Unit of measurement	Value	
Capital costs			
A plant for the production of fuel pellets, with a capacity of		from wood	from ag-waste
500 kg/h		10	8
700 kg/h	mln RUB	12	10
1 000 kg/h		14	12
1 500 kg/h		17	15
2 000 kg/h		20	18
Warehouse construction	million RUB/m ²	0.004	
Operating costs			
Payroll fund	million RUB/person per year	0.8	
Electricity	RUB/kWh	5.0	
Other expenses	% of equipment cost	3	
Pine sawdust	RUB/t	1 000	
Straw	RUB/t	5 000	
Mixed grasses	RUB/t	5 000	
Torrefied sunflower husk	RUB/t	4 500	
Lignin (BPPM waste)	RUB/t	0	
Other indicators			
Discount rate	%	10	
Project lifetime	years	15	
Property tax	%	2	

TABLE 5. Change in Project Investment Indicators for Pellets with Different Compositions Depending on Raw Material Prices

Pellet composition	NPV at different raw material prices (% of current price), million RUB			DPP at different raw material prices (% of current price), years			IRR at different raw material prices (% of current price), %		
	0	50	100	0	50	100	0	50	100
	Pine sawdust (%) / lignin (%)								
100/0	129.7	57.4	-14.8	2.0	3.8	62.9	100.64	51.79	-
95/5	129.7	61.0	-7.6	2.0	3.6	24.6	100.64	54.24	2.39
88/12	129.7	66.1	2.5	2.0	3.4	13.3	100.64	57.68	12.20
77/23	129.7	74.0	18.4	2.0	3.1	7.7	100.64	63.06	24.62
Straw (%) / mixed grasses (%)									
100/0	138.7	18.3	-102.2	1.8	7.5	-	112.02	25.27	-
50/50	138.7	-282.8	-704.3	1.8	-	-	112.02	-	-
Torrefied sunflower husks (%) / straw (%)									
15/85	138.7	-33.3	-205.3	1.8	-	-	112.02	51.79	-
10/90	138.7	-16.3	-171.3	1.8	130.0	-	112.02	-	-

determined as the smallest integer for which the cumulative discounted cash flows become non-negative:

$$\sum_{t=0}^{DPP} \frac{NCF_t}{(1+r)^t} = \sum_{t=0}^n I_t, \tag{2}$$

and the internal rate of return (IRR):

$$\sum_{t=0}^n \frac{NCF_t}{(1+IRR)^t} - \sum_{t=0}^n I_t = 0. \tag{3}$$

Furthermore, to assess the cost of thermal energy derived from the pellets, the Levelized Cost of Pellets (LCOP) is calculated, following the methodology [24]:

$$LCOP = \frac{\sum_{t=1}^n (C_t + I_t)(1+r)^{-t}}{\sum_{t=1}^n P_t(1+r)^{-t}}, \tag{4}$$

where C_t is the annual operating and maintenance costs in year t , million RUB/year; I_t is the annual capital

investment t , million RUB/year; P_t is the annual pellet output, tonnes/year.

The economic calculations were performed using the baseline parameters provided in Table 4.

B. Results of the Economic Assessment of Fuel Production

Assessment of the investment attractiveness for a pellet plant with a capacity of 1 000 kg/h and examination of current raw material prices (Table 4) reveal that NPV values are negative for all pellet compositions under base-case pricing except for pellets made from 88% sawdust and 12% lignin and from 77% sawdust and 23% lignin. For these compositions, the NPV amounts to RUB 2.5 million and RUB 18.4 million, respectively.

However, given the tightening of Russian waste management regulations in recent years (e.g., Federal Law

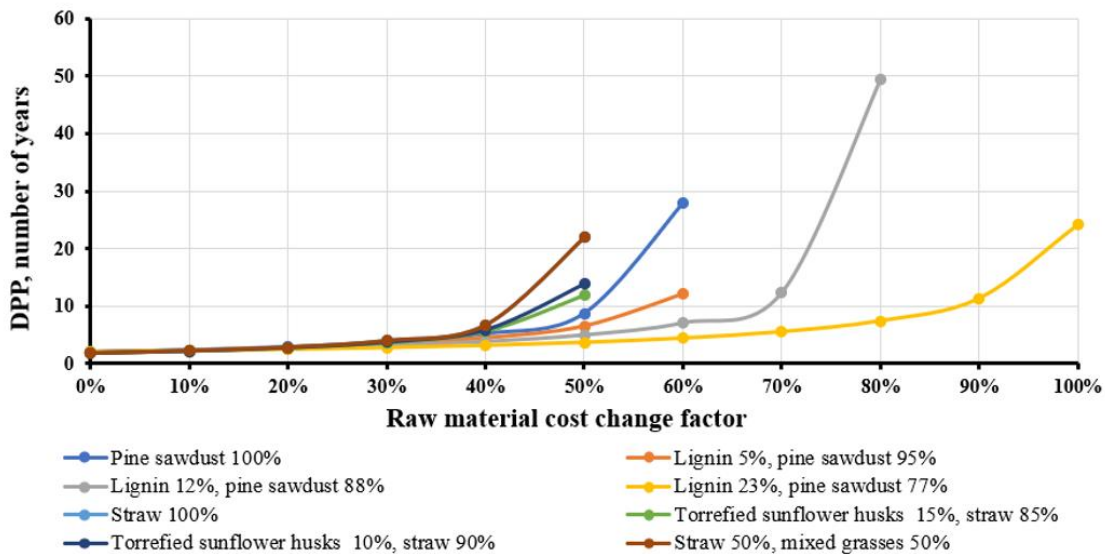


Fig. 4. Change in DPP for pellets with different compositions depending on raw material prices.

No. 89-FZ amendments, extended producer responsibility), it is reasonable to assume that certain biomass residues, particularly industrial by-products such as lignin or sawdust from integrated mills, may become effectively free or even incentivized (negative-cost) feedstocks, as enterprises seek to avoid disposal fees or environmental penalties.

Under the “zero-cost feedstock” scenario (i.e., raw material cost = 0% of values in Table 4), the project economics improve dramatically:

- DPP ≤ 2 years for all 8 technically viable formulations;
- NPV (15-year horizon) ranges from RUB 129.7 million to RUB 138.7 million;
- IRR reaches 100.6 % to 112.0 %, indicating extremely high profitability.

Under a 50% raw material cost scenario (midway between base case and zero-cost):

- NPV improves from – RUB 282.8 million to +74.0 million RUB (i.e., 5 of 8 blends become NPV-positive);
- DPP ranges from 3.1 to 130.0 years (only 5 blends remain uneconomical within 15 years);
- IRR rises from 25.3 to 63.1%, with higher-lignin blends again outperforming others.

Table 5 summarizes how key investment indicators (NPV, DPP, IRR) vary with raw material cost levels

(expressed as % of base-case prices in Table 4), across the 8 RDF pellet formulations.

Figure 4 shows the change in the Discounted Payback Period (DPP) of the RDF pellet production facility for different raw material prices.

The study demonstrates that pellet production becomes economically viable, achieving payback within 15 years under the following conditions:

- Pellets composed of 95–100% sawdust and 0–5% lignin: feasible when raw material costs are reduced to 90% of the base-case values (Table 4);
- Pellets composed of 77–88% sawdust and 12–23% lignin: feasible when raw material costs are 100% of the base-case values;
- Pellets composed of 15% torrefied sunflower husks and 85% straw: feasible when raw material costs are reduced to 30% of the base-case values;
- Pellets composed of 10% torrefied sunflower husks and 90% straw: feasible when raw material costs are reduced to 40% of the base-case values;
- Pellets composed of 100% straw: feasible when raw material costs are reduced to 50% of the base-case values;
- Pellets composed of 50% mixed grass and 50% straw: feasible when raw material costs are reduced to 10% of the base-case values.

The analysis of LCOP (Levelized Cost of Pellets) and

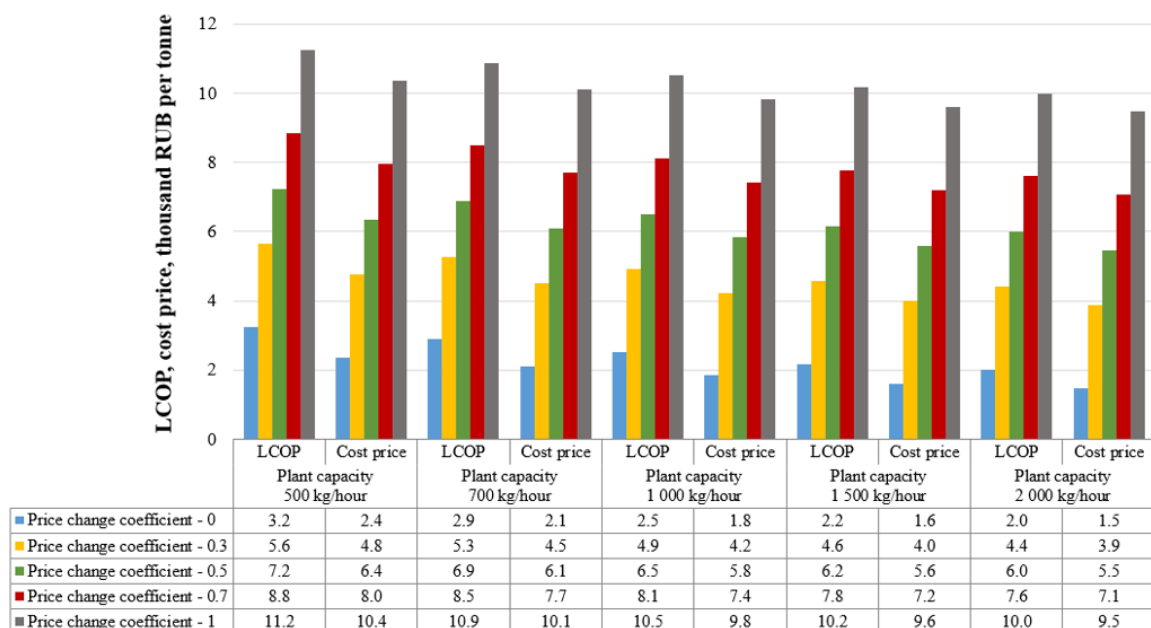


Fig. 5. Change in LCOP and production cost of pellets made from 100% sawdust depending on raw material prices and plant capacity.

unit production cost confirms a pronounced economies-of-scale effect: both metrics decline significantly as plant capacity increases (Figures 5–9). The breakeven threshold (i.e., minimum pellet selling price for $NPV = 0$) shifts downward with scale, though the magnitude depends on

formulation.

Specifically, when production capacity rises from 500 kg/h to 2 000 kg/h (i.e., 4× scale-up), unit production costs decrease as follows (Table 6).

The wide cost-reduction range (e.g., 14.2–37.5%)

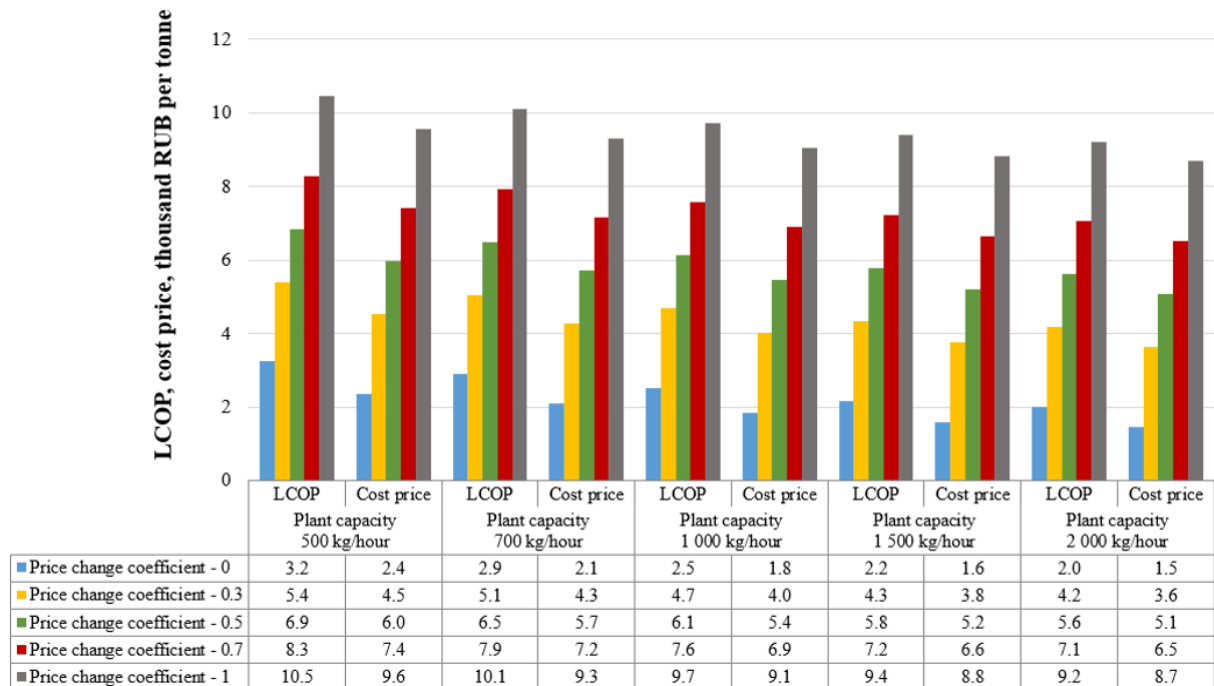


Fig. 6. Change in LCOP and production cost of pellets consisting of 95% sawdust and 5% lignin depending on raw material prices and plant capacity.

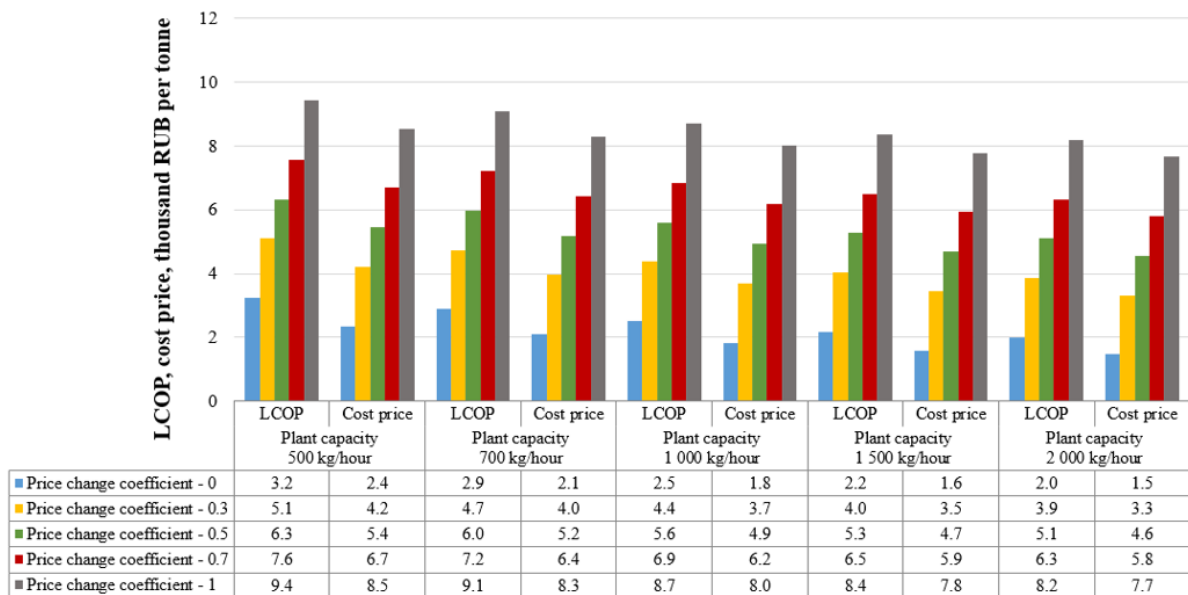


Fig. 7. Change in LCOP and production cost of pellets consisting of 88% sawdust and 12% lignin depending on raw material prices and plant capacity.

reflects varying assumptions in operating hours, labor efficiency, and maintenance intensity at different scales.

Across all formulations, economies of scale significantly reduce production costs, but the magnitude of this benefit is strongly formulation-dependent. Pine sawdust/lignin blends, particularly those containing $\geq 23\%$ lignin, demonstrate the steepest cost reduction (up to

37.5%) with scale-up, consolidating their status as the most economically resilient and scalable option. This advantage stems not only from lignin's binding properties reducing reliance on external additives but, crucially, from its potential to serve as a negative-cost or zero-cost waste stream, transforming a disposal liability feedstock into a value-added one.

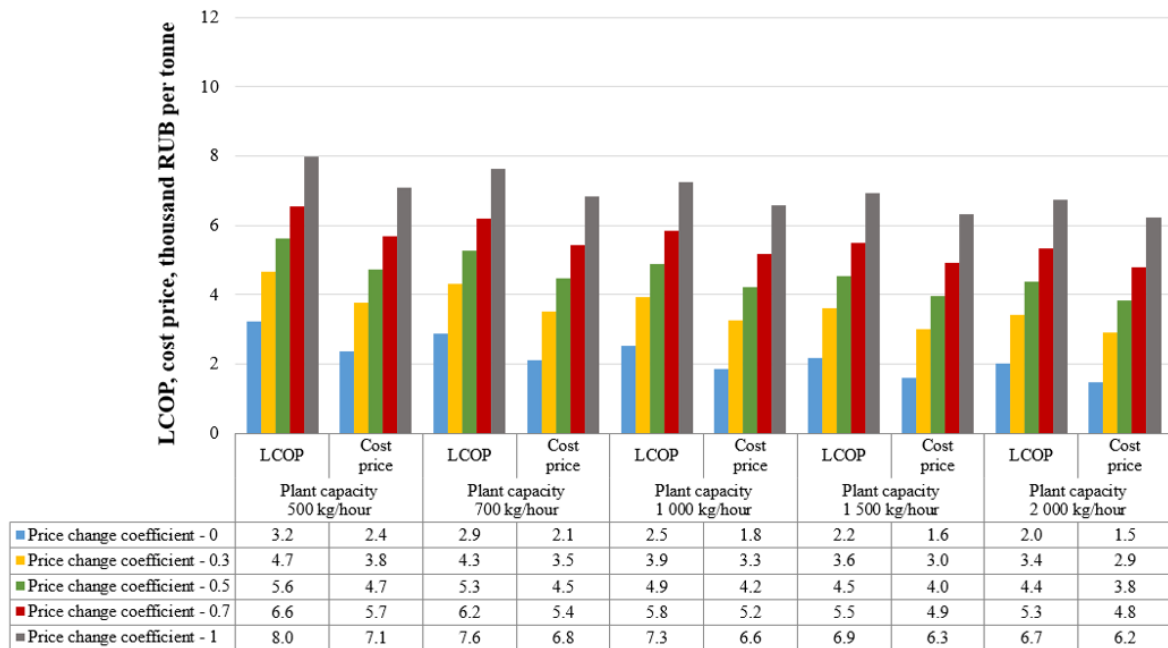


Fig. 8. Change in LCOP and production cost of pellets consisting of 77% sawdust and 23% lignin depending on raw material prices and plant capacity.

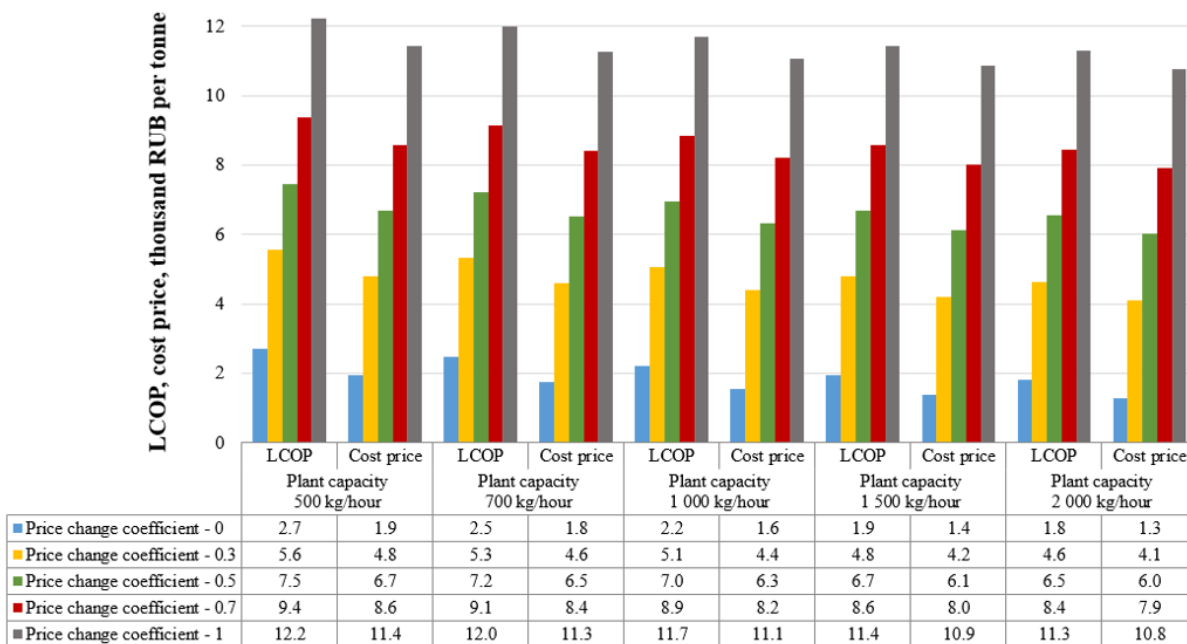


Fig. 9. Change in LCOP and production cost of pellets consisting of 90% straw and 10% mixed grasses depending on raw material prices and plant capacity.

TABLE 6. Range of Cost Reduction Depending on Production Capacity and RDF Pellet Composition

Pellet composition	Cost reduction range, %
Pine sawdust (%) / lignin (%)	
100/0	12.0–37.5
95/5	12.4–37.5
88/12	13.1–37.5
77/23	14.2–37.5*
Straw (%) / mixed grasses (%)	
100/0	6.5–34.4
50/50	2.1–34.4
Torrefied sunflower husks (%) / straw (%)	
15/85	4.8–34.4
10/90	5.2–34.4

*Largest benefit reflecting lignin's dual role as a low-cost binder and a waste valorization driver

In contrast, agro-pellets (straw-, grass-, and husk-based blends) exhibit markedly smaller cost savings (2.1–34.4%), even at larger capacities. Their economic viability remains highly vulnerable to volatile raw material prices and logistical constraints, highlighting the necessity of targeted policy interventions, such as subsidies for agricultural residue collection, waste-to-energy premiums, or integration into existing agro-logistics and co-firing schemes to enhance competitiveness.

Critically, the analysis reveals that feedstock cost structure and plant scale are dominant determinants of commercial feasibility, far outweighing the influence of marginal variations in pellet durability (e.g., 92.3% vs. 96.1%) or heating value (± 1 –2 MJ/kg). Economic performance is extremely sensitive to raw material pricing: even modest reductions (e.g., to 50–60% of current levels) can shift NPV from deeply negative to highly positive and reduce DPP from >20 years to <2 years.

Therefore, strategic policy measures aimed at de-risking feedstock supply, such as incentivizing industrial lignin valorization, enforcing landfill diversion for biomass residues, introducing carbon pricing, or establishing regional waste-exchange platforms, are not merely beneficial but essential for unlocking the large-scale deployment of RDF pellet technologies in Russia. Without such enablers, even technically sound formulations risk remaining confined to pilot-scale demonstrations.

V. CONCLUSION

This study assessed the regional bioenergy potential of wood and crop residues across Russia, revealing that despite their large annual availability (~11.2 million tonnes in 2022), only a small fraction (0.42% of national fuel use)

is currently recoverable due to economic and technological barriers. The highest potential lies in the Siberian and Northwestern Federal Districts, where forest residues could offset up to 0.66% and 0.56% of local fuel demand, respectively highlighting the need for region-specific strategies and supportive policies.

Composite RDF pellets made from sawdust, lignin, sunflower husk, straw, and grasses were successfully developed and tested. Formulations meeting a mechanical durability threshold of $\geq 93\%$ comply with GOST 33103.2–2017 and are suitable for commercial use. Optimal blends include up to 23% lignin in sawdust-based pellets, at least 50% straw in grass mixtures, and limited sunflower husk ($\leq 10\%$) to maintain quality.

Economic viability hinges primarily on feedstock costs. Sawdust – lignin pellets are feasible only if lignin is sourced as a zero-cost by-product. Agro-pellets require significantly lower raw material prices than current market levels (straw \leq RUB 2 500/t, grass \leq RUB 450/t, and sunflower husk \leq RUB 1 500/t). Overall, integrating waste streams and optimizing composition are key to advancing cost-effective, sustainable bioenergy in Russia.

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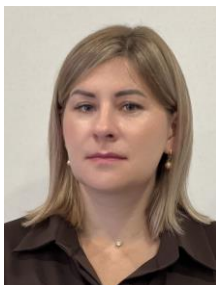
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