

Research Article

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**ASSESSMENT OF AGRICULTURAL WASTE
ENERGY POTENTIAL FOR CIRCULAR ECONOMY
AND BIOFUEL PRODUCTION**

Background. The transformation of agro-industrial waste into a strategic resource for energy decentralisation is crucial. In view of modern security challenges and the European Green Deal, there is a growing need for agro-industrial enterprises to transition to closed circular bioeconomy cycles, where intellectual capital and digitalisation serve as the basis for innovative progress.

Purpose. The purpose is to provide a comprehensive assessment the potential for biofuel production from waste in the agricultural sector of Ukraine and justify its strategic role in ensuring energy independence, using a model to assess the technical and energy potential of biomass, taking into account environmental and logistical constraints.

Findings. A model of the integrated technical and energy potential of the agro-industrial complex biomass was developed and tested based on ecological and technological screening principles for the period 2022-2025. The methodology considers the agro-ecological qualification (removal of no more than 25–30% of plant residues to preserve humus) and the institutional barrier of large-scale commercialisation (screening of dispersed waste from the private livestock sector), based on which the commercial potential of Ukrainian agro-biomass was determined at the level of 4.63 million tons of oil equivalent (toe) and its regional decomposition was carried out. The involvement of food industry enterprises (sugar and alcohol plants) as logistics hubs for biomethane and digestate production has optimised supply chains and reduced logistics costs by 30–40% compared to the decentralised collection of distributed biomass. Due to the concentration of significant volumes of homogeneous waste at the industrial sites of these enterprises, the maximum methane yield is achieved through co-fermentation, increasing the investment attractiveness of biogas projects and accelerating their payback.

Implications. The effective conversion of agricultural waste into biofuels can significantly reduce the consumption of fossil resources (natural gas and coal) in local heat and power supply systems. The main barriers to the development of circular models are a lack of long-term investment capital and institutional restrictions on the integration of biomethane into the network. The practical significance of the results lies in the development of applied tools for government agencies and businesses to support regional energy development strategies and climate neutrality programs.

Keywords: Agricultural Waste, Agro-Industrial Complex, Biomass, Circular Economy, Energy Potential.

1. Introduction.

Given the worsening geopolitical situation and the current state of the global energy market, countries are actively seeking ways to strengthen their energy security and decarbonise their economies. One of the most promising directions for countries with developed agricultural sectors, such as Ukraine, is the transition to a circular economy model in which agro-industrial complexes are recognised as valuable energy resources. The production of biofuels (biomethane, solid fuels, and bioethanol) from crop and livestock by-products can simultaneously address waste disposal issues, reduce reliance on fossil fuels, and mitigate greenhouse gas emissions. However, to realise this potential, a thorough analysis of the resource base, technological capabilities, and economic feasibility is necessary.

In the context of global energy instability and rising climate change demands, the development of bioenergy has become a strategic priority for agrarian-oriented countries (Venkatramanan et al., 2021). The use of agro-industrial complex (AIC) waste for energy generation not only diversifies the energy balance but also ensures the sustainable development of rural areas. The economic assessment of environmental protection activities within Ukraine's sustainable development concept, as presented in Kaletnik's (2025) research, indicates the need to integrate environmental measures into the overall agricultural production strategy.

The environmental feasibility and transition to a "green" economy through the production of biofuels from waste to achieve climate neutrality have been thoroughly analysed (Gontaruk et al., 2024; Hontaruk et al., 2024), and the need for a transition to biofuel production has been stated. Priority areas for development include adapting production systems to bio-economy principles, implementing environmentally friendly technologies, and establishing efficient market channels for innovative bio-based products. The effectiveness of these processes largely depends on the level of human capital, technological capabilities, and digital maturity of agro-industrial enterprises.

Under such conditions, intellectual capital becomes an important factor in the digital transformation of the agricultural sector, facilitating the adoption of innovation and improving enterprises' adaptability to a rapidly changing economic environment. The substantial biomass resource potential of Ukraine, its climate commitments, and the growing need for decentralised energy systems further emphasise the relevance of this study.

2. Literature Review.

The theoretical basis for the study of renewable energy sources in the agricultural sector is formed at the intersection of environmental safety, the circular economy, and the strategic management of agro-industrial enterprises. A thorough discussion is underway to find a balance between increasing the generation of alternative fuels and preserving the ecosystem potential of rural areas.

Significant attention has been paid to biomass inventory, the assessment of its energy equivalent, and the development of decentralised energy supply models, considering agricultural by-products not as production waste but as highly efficient economic resources. The assessment of biofuel production potential should be based on an analysis of crop and livestock residues, which is key to strengthening energy independence and transitioning to a circular economy (Damian et al., 2024).

The agricultural sector possesses significant biomass resources. However, their effective conversion into energy requires the introduction of innovative technologies and consideration of the environmental standards of the European Green Deal (Honcharuk et al., 2026). Particular attention is paid to the economic feasibility of various biofuel types. Kaletnik et al. (2021) demonstrated that using solid biofuels derived from agricultural by-products (straw and husks) is one of the most cost-effective ways to replace fossil fuels in heating systems. Simultaneously, Vasileiadou (2024) and Talavyria (2025) emphasised the potential of biogas technologies to transform organic waste into high-quality biomethane and organic fertilisers, thereby addressing the industry's energy and environmental problems.

As part of post-war reconstruction, research priorities focus on restructuring production in line with bioeconomy principles, implementing green technological solutions, and developing effective sales channels (Toplicean & Datcu, 2024). Ukraine has the potential to use approximately 11–12 million hectares of land (Tokarchuk et al., 2022). Previous studies have emphasised that the effectiveness of marketing tools in the bioenergy industry depends on the level of human and technological development of agro-industrial enterprises. Intellectual capital is the basis for the digitalisation of the agro-industrial complex, ensuring not only innovative progress but also flexible adaptation to the conditions of the modern digital economy (Bondarenko et al., 2026).

The macro-level socioeconomic and environmental implications of accelerating biofuel production position Ukraine as a strategically important player in the international bioenergy arena. Pryshliak et al. (2021) emphasise that the systemic development of the biofuel sector not only mitigates global climate risks but also stimulates rural regional economies by generating new jobs, reducing dependency on imported energy resources, and improving the overall trade balance. The international dimension underscores the need to transform traditional linear agricultural practices into advanced waste-to-energy systems (Damian et al., 2024).

The transition towards a circular economy requires the development of highly resource-efficient business models that capitalise on the waste-to-energy nexus. By implementing such closed-loop frameworks, agro-industrial enterprises can significantly minimise environmental degradation while simultaneously securing localised, decentralised energy streams from organic residues.

The practical deployment of these circular principles is deeply intertwined with the optimisation of biogas technologies and their secondary outputs. While the primary focus often remains on biomethane generation, the economic and environmental value of the by-products cannot be overlooked. Lohosha et al. (2023) demonstrated the high economic efficiency of using digestate from biogas plants as a biofertiliser for crops.

This practice directly aligns with the rigorous environmental standards of the European Green Deal, offering a viable alternative to synthetic fertilisers, restoring soil fertility, and completing the nutrient cycle in agricultural ecosystems.

Ultimately, balancing the dual priorities of energy independence and food security remains a critical focus of contemporary research. Tokarchuk et al. (2022) argue that resolving the “food versus fuel” dilemma in Ukraine requires a highly optimised land-use approach, ensuring that land allocated to bioenergy crops does not jeopardise national or global food supplies. Addressing these multilayered challenges demands a synthesised strategy in which technological innovation, intellectual capital, and ecological responsibility converge to drive the sustainable post-war recovery of the agro-industrial complex.

It should be noted that, despite in-depth studies of individual aspects of the bioeconomy’s functioning, a comprehensive, spatially differentiated assessment of the real energy potential of agricultural waste (Awogbemi & Kallon, 2022; Yrjälä et al., 2022) is lacking, one that accounts for environmental determinants and current macroeconomic conditions. The presence of a significant theoretical basis is accompanied by a shortage of pragmatic calculations that would integrate strict requirements for maintaining the humus balance and current logistical constraints into a single model of the regional distribution of fuel resources.

The outlined state of development of the problem determines the relevance, structure, and logic of this research. This study aims to provide an assessment of the potential for biofuel production from agricultural sector waste and substantiate its strategic role in ensuring the state’s energy independence. To achieve this goal, the following research questions were identified and addressed:

RQ 1. Analyse the structure and volumes of the main types of agricultural waste (plant residues and livestock waste) by region.

RQ 2. Assess the technical and energy potential of biomass while accounting for the need to preserve soil fertility and logistical constraints.

RQ 3. Determine the share of replacement of traditional energy resources (natural gas, coal, and petroleum products) through the introduction of biofuel technologies.

RQ 4. Identify key barriers (economic, legislative, and technical) and formulate recommendations to stimulate bioenergy development in the agricultural sector.

Solving the outlined tasks will not only enable the quantitative assessment of the agricultural sector's resource base but also develop a holistic vision for transforming agro-industrial complex waste into a strategic reserve for energy independence. This study focuses on refining methodological approaches for calculating the energy equivalent of biomass, taking into account modern agroecological requirements and the territorial distribution of raw materials.

The practical significance of the results lies in their potential use by state bodies and business entities to develop regional energy strategies. This will contribute to the creation of closed production cycles, which is critically important for increasing the competitiveness of domestic agribusiness in the context of integration into the European economic space and fulfilling climate-neutral obligations.

3. Methodology.

The methodological basis of the study is a systematic approach to assess the resource potential of the agro-industrial complex for the formation of decentralised renewable energy sources. The research and analytical calculations were performed according to a four-stage procedure: Stage 1 [Database formation] → Stage 2 [Potential Assessment] → Stage 3 [Substitution calculation] → Stage 4 [Identifying barriers]. To achieve the study's goal, we developed and tested our own methodology to assess the integrated technical and energy potential of biomass in the agricultural sector.

Unlike existing approaches that often assess biomass in isolation or calculate abstract theoretical potential, the proposed methodology is based on the principles of ecological and technological screening. The model cuts off that part of the straw that the soil needs to reproduce the humus.

Livestock waste generated in individual households cannot be profitably incorporated into industrial production due to its high dispersion. The integral technical and energy potential of replacing fossil fuels with agrobiomass (E_{total}), expressed in tons of oil equivalent, was calculated according to:

$$E_{total} = [\sum_i^n (V_i * K_{posi} * K_{eco} * Q_{ni}^r)] + [\sum_{j=1}^m (N_j * K_{comj} * M_j * Y_{bmj} * \omega)] \quad (1)$$

where,

V_i – gross harvest of the main product of the i -th agricultural crop (wheat, corn, sunflower, etc.) for the reporting period, tons;

K_{posi} – residue-to-product ratio of the i -th crop, indicating agricultural residues generated per unit mass of the main product.;

K_{eco} – ecological and logistical constraint coefficient, indicating the share of crop residues excluded from energy use and retained in the field for soil conservation and humus balance (assumed constant at 0.25–0.30);

Q_{ni}^r – lower heating value of dry crop residues of the i -th crop, expressed in tons of oil equivalent per ton of biomass (toe/t);

N_j – livestock population of the j -th animal (cattle, pigs, poultry, etc.), heads;

K_{comj} – industrial concentration coefficient reflecting the share of animals in large-scale commercial systems (0.85–0.90 poultry, 0.60–0.65 pigs, 0.25–0.30 cattle), indicating the fragmented structure of cattle farming;

M_j – annual manure production per head of the j -th animal category, t/year;

Y_{bmj} – specific yield of purified biomethane (100% CH₄) from anaerobic digestion of manure, m³/t of substrate;

ω – energy equivalent of converting cubic meters of biomethane into tons of oil equivalent (1000 m³ biomethane approximately 0.85 toe).

The formula integrates two autonomous raw material blocks: by-products of crop production and organic waste from livestock farming and industrial processing. To determine the share of substitution of traditional fuel and energy resources ($Z_{\%}$), the indicator of total energy potential (E_{total}) obtained from the formula was compared with the actual volumes of consumption of natural gas, coal, and fuel oil by regional consumers:

$$Z_{\%} = \frac{E_{total}}{PE_{trad}} * 100 \quad (2)$$

where,

PE_{trad} – total consumption of traditional fuels in the region (in oil equivalent).

The application of this development enabled the final assessment of Ukraine’s biomass technical and energy potential at 4.63 million tons of oil equivalent, along with the spatial decomposition into regional clusters.

4. Results.

The practical implementation of the decarbonisation strategy and strengthening of Ukraine's energy security within the framework of the circular economy model requires, first, an objective and detailed assessment of the available raw material base. The transition from linear resource use to closed cycles, in which by-products and waste from the agro-industrial complex are considered valuable energy resources, necessitates a comprehensive analysis of the volume generated.

To provide a holistic vision of the transformation of agricultural biomass into a strategic reserve of energy independence, this section presents a quantitative, structured assessment of the production potential of the main biofuel types (solid fuels, biomethane, bioethanol, and biodiesel).

Table 1 indicates a powerful yet fluctuating raw material base during the study period. The grain wedge is the fundamental basis for generating solid biofuels and crop residues. The production volumes of grain and leguminous crops demonstrated wave-like dynamics. After reaching a peak in 2023 (60.70 million tonnes) and a slight decline in 2024 (to 56.43 million tonnes), the figure rose again in 2025 (61.04 million tonnes).

This increase in production (by almost 8.2% compared to 2024) confirms a steady trend towards higher potential volumes of straw and other crop by-products suitable for industrial combustion, pelleting and briquetting.

Table 1. Production Volumes of Agricultural Crops in Ukraine by Producer Categories, 2022–2025 (million tons).

Year	Type of agricultural holding	Sugar beet (for processing)	Cereal and leguminous crops	Winter rapeseed and colza (spring rapeseed)	Sunflower seeds	Soya beans
2022	Total	9,94	54,75	3,32	11,35	3,46
	Enterprises	9,41	42,16	3,30	9,76	3,18
	Households	0,53	12,59	0,02	1,59	0,28
2023	Total	13,18	60,70	4,19	12,88	4,80
	Enterprises	12,47	46,74	4,17	11,08	4,41
	Households	0,71	13,96	0,02	1,80	0,39
2024	Total	12,80	56,43	3,61	11,01	6,07
	Enterprises	12,11	43,45	3,59	9,47	5,58
	Households	0,69	12,98	0,02	1,54	0,49
2025	Total	11,69	61,04	3,21	10,24	4,98
	Enterprises	11,06	47,61	3,20	8,81	4,58
	Households	0,63	13,43	0,01	1,43	0,40

Source: based on the State Statistics Service of Ukraine (2026).

In this sector, households consistently account for approximately 20–25% of the gross harvest (12.59-13.96 million tonnes annually). This part of the straw residue is too dispersed, making its industrial extraction financially impractical and potentially leaving it within the scope of private use for the production of solid biofuels or natural soil mineralisation (Table 2).

The agricultural production sector, which is crucial to the liquid biofuels industry (bioethanol, biodiesel) and to highly concentrated biomethane, is characterised by scale. The sunflower harvest remained stable, fluctuating between 10.24 and 12.88 million tons, ensuring an uninterrupted supply of valuable energy raw materials, such as sunflower husks.

Table 2. Structure and Volume of Agricultural Waste Generation (Crop Residues and Livestock Waste) by farm category, thousand tons.

	All agricultural holdings		Enterprises		Households	
	2025	2025 in % to 2024	2025	2025 in % to 2024	2025	2025 in % to 2024
Cereal and leguminous crops	11786,9	105,8	8699,2	108,4	3087,7	99,2
wheat	5166,1	105,6	4015,5	107,5	1150,6	99,5
wheat winter	5000,4	106,1	3902,2	108,0	1098,2	99,6
wheat spring	165,7	92,7	113,3	90,5	52,4	97,7
maize	4540,8	111,1	3599,5	114,6	941,3	99,7
barley	1385,6	98,9	613,4	98,0	772,2	99,6
barley winter	592,2	104,5	417,6	105,5	174,6	102,1
barley spring	793,4	95,1	195,8	85,1	597,6	98,9
rye	64,9	92,1	28,9	87,7	36,0	95,9
rye winter	64,4	92,1	28,8	87,8	35,6	96,0
rye spring	0,5	85,5	0,1	75,0	0,4	88,4
oat	137,9	79,2	38,6	60,0	99,3	90,4
buckwheat	57,1	62,7	29,0	47,8	28,1	92,3
sorghum	19,9	109,7	16,2	109,2	3,7	111,8
millet	33,5	35,3	24,1	28,3	9,4	96,0
rice	2,8	91,1	2,8	91,1	–	–
leguminous crops	370,3	124,4	323,6	128,9	46,7	100,0
bean	48,2	94,6	14,5	84,2	33,7	99,8
pea	278,8	132,0	266,2	133,9	12,6	101,3
Industrial crop	8770,2	93,5	7861,4	92,8	908,8	100,1
Soya beans	2079,8	76,5	1910,8	75,2	169,0	94,1
Curly flax (oil)	65,6	121,1	65,5	121,1	0,1	102,4
Mustard	13,9	32,7	13,2	31,6	0,7	96,8
Winter rapeseed and colza	1209,6	96,7	1204,0	96,8	5,6	80,3
(spring rapeseed)						
winter rapeseed	1179,8	97,0	1174,8	97,1	5,0	78,9
colza (spring rapeseed)	29,8	87,1	29,2	87,0	0,6	92,5
Sunflower seeds	5161,1	102,8	4442,7	103,0	718,4	101,9
Fibre flax	0,5	124,0	0,5	124,0	–	–
Hemp	3,0	219,8	3,0	219,8	–	–
Sugar beet (for processing)	198,7	78,3	188,0	77,7	10,7	92,4
Fodder crops	1173,8	95,3	322,2	95,7	851,6	95,2
Fodder beet	144,1	95,8	0,1	80,2	144,0	95,9
Fodder melon crops	36,1	97,5	0,2	98,2	35,9	97,5
Fodder maize	189,8	99,3	181,3	99,4	8,5	96,7

Source: based on the State Statistics Service of Ukraine (2026).

The soybean sector saw rapid growth until 2024, when it reached an all-time high of 6.07 million tons, but in 2025, it declined to 4.98 million tons (a 17.9% reduction). The dynamics of the rape harvest (winter and spring) mirror those of industrial crops, with a decline in 2025 to 3.21 million tonnes after a maximum of 4.19 million tonnes in 2023.

Factory sugar beet production showed a significant increase in 2023 (13.18 million tonnes compared to 9.94 million tonnes in 2022). During 2024–2025, the collection volumes decreased slightly to 12.80 million tons and 11.69 million tons, respectively.

Despite this decrease, current volumes are sufficient to provide sugar factories with raw materials, which, in turn, allows for the centralised accumulation of significant volumes of associated processing waste (beet pulp and molasses) directly at logistics hubs for the production of biomethane and digestate.

An analysis of the structure and dynamics of waste generation indicates that Ukraine's agricultural sector provides a powerful, albeit somewhat unbalanced, base for renewable energy development. Due to high yields, grain and leguminous crops confidently remain the main source of ecological raw materials.

In 2025, they produced over 11.7 million tons of crop residues, showing a pleasing growth of almost 6%. At the same time, the share of biomass generated by wheat and corn showed record growth rates of over 11% in residues, which opens up excellent prospects for large enterprises to collect industrial waste. Industrial crops decreased their contribution by 6.5% this year, providing approximately 8.7 million tons of raw materials. This decrease was due to a significant reduction in the production of soybean residues and sugar beets in factories.

Sunflower production remained stable and consistent, exceeding 5.1 million tons. This proves that husks and stems remain the most popular and financially profitable resources for the production of fuel pellets and briquettes. Fodder crops have unique characteristics, with their residues totalling just over 1.1 million tons, and this sector depends on private household farms for almost three-quarters of its output.

As fodder beets and melons are primarily grown in personal gardens, collecting such waste on an industrial scale is quite difficult. Therefore, to deploy powerful bioenergy projects, the state and businesses should focus on large agricultural enterprises that centrally accumulate maize, wheat, and sunflower waste, thereby minimising complex logistics costs.

The analysis in Table 3 shows that the biogas efficiency depends directly on the dry matter concentration in the substrate, which determines the amount of organic matter available for fermentation. The absolute leader in terms of energy capacity is molasses from sugar factories, which, due to its high dry matter content (76–80%), provides a colossal gas yield of 390–400 m³/t. High fuel efficiency is also demonstrated by chicken litter and corn silage, which, owing to their optimal biomass structure, guarantee a stable release of 150–200 m³/t of high-quality energy per ton.

Table 3. Technological Parameters and Energy Potential of Substrates of the Agro-Industrial Complex for Biogas Generation (2026).

Raw material name	DM, %	Biogas output, m ³ /t	CH ₄ content, %
Beet pulp (after storage)	10-17	55-90	54-55
Beet pulp (pressed)	18-22	95-115	54-55
Beet pulp (fresh)	6-9	34-50	54-55
Cattle manure (flush system)	5-6	15-18	55-58
Cattle manure (litter)	14-17	42-50	55-58
Chicken manure (unlittered)	25	90-100	58-60
Chicken droppings (litter)	60	150-160	58-60
Molasses (from sugar factories)	76-80	390-400	54-55
Pig manure	4-5	13-17	57-60
Beer grains	22-24	103-115	55-59
Distilled dregs (corn kernels)	6-11	46-52	54-56
After-alcohol bard (molasses)	11-12	42-45	54-56
After-alcohol dregs (wheat)	6-11	42-49	54-56
Corn Silage	33	180-200	52-54

Source: based on the Bioenergy Association of Ukraine (2025).

Substrates for beet sugar and alcohol production have moderate energy potential, which varies depending on the technology used to prepare the raw materials. The mechanical dehydration of fresh beet pulp to a pressed state increases the dry matter content to 18–22% and the specific biogas yield by more than twice, to 95–115 m³/t. Post-alcohol lees and beer grains ensure a stable course of anaerobic fermentation owing to their balanced chemical composition, emitting gas with a high methane content.

Livestock effluents, particularly pig manure and cattle manure from flushing systems, have the most modest gas output rates, not exceeding 18 m³/t, owing to excessive moisture and low dry matter concentration (4–6 %) (Bioenergy Association of Ukraine, 2025).

However, littered cattle manure and unlittered chicken manure demonstrated significantly higher fuel efficiencies owing to lower water dilution.

The poorest liquid livestock waste is a diluent for dry industrial substrates, thereby justifying the feasibility of implementing co-fermentation technology to maximise methane yield. The dynamics of animal populations and the volume of manure and litter produced in Ukraine from 2022 to 2025 indicate significant structural changes in the livestock sector, which directly affect the stability of the raw material base for the biogas industry.

The most significant reduction in raw material potential was observed in the cattle sector, where herd size decreased from 2.30 million heads in 2022 to 1.80 million in 2025. Given the highest specific waste generation rate among all analysed animal species, which is 11 tons per head per year, this drop led to a significant decrease in the gross volume of cattle manure from 25.30 to 19.80 million tons. Cattle remain the leading source of total organic waste in the agro-industrial complex (Table 4).

The pig sector during the study period showed relative stability, with a slight peak in 2023, when the livestock population reached 5.15 million heads, and the total manure volume reached 9.27 million tons. A moderate decline characterised the following years, and by 2025, the number of pigs decreased to 4.64 million heads, ensuring an annual generation of 8.35 million tons of liquid organic waste at a rate of 1.8 tons per animal.

Poultry farming was the only agricultural sector to demonstrate overall positive dynamics and flexibility amid market fluctuations. After a temporary dip in 2024, the number of poultry of all species in 2025 reached its highest level in 4 years, at 121.40 million heads. Despite a minimum waste generation rate of 0.055 tons per head per year, Ukrainian poultry farms generated a record 6.68 million tons of valuable chicken manure due to the large number of livestock.

Table 4. Animal Population and Organic Waste Generation by year (2022–2025).

Animal species	Year	Livestock (million heads)	Production rate (tons/head/year)	Total waste volume (million tons per year)
Cattle	2022	2,30	11.0	25,30
	2023	2,18		23,98
	2024	2,05		22,55
	2025	1,80		19,80
Pigs	2022	5,02	1.8	9,04
	2023	5,15		9,27
	2024	4,90		8,82
Poultry (all species)	2022	116,00	0.055	6,38
	2023	120,50		6,63
	2024	118,20		6,50
	2025	121,40		6,68

Source: based on the Ministry of Agrarian Policy of Ukraine (2005).

Given the dry matter concentration in manure, the poultry sector demonstrates investment potential for expanding the capacity of biogas plants. The spatial distribution of bioenergy resources enables assessment of the potential to transform the agricultural sector into a decentralised energy system.

The potential structures in Table 5 are based on agroecological constraints limiting straw removal to 25–30% to preserve soil humus balance. The gross biomass energy potential is estimated at 9.26 million tons of oil equivalent.

The calculations were adjusted for the logistical availability coefficient, focusing exclusively on consolidated waste streams from large agricultural enterprises to eliminate the risk of biomass dispersion in households. The regional structure of biofuel production potential in Ukraine in 2025 is characterised by pronounced spatial differentiation and significant volumes of renewable energy resources, with a commercial potential, based on ecological and technological screening, estimated at 4.63 million tons of oil equivalent.

Table 5. Regional Structure of Biofuel Production Potential in Ukraine, 2025 (thousand tons of oil equivalent).

Region	Bioethanol	Biodiesel	Solid biofuels	Biogas	Total	Share, %
Vinnitsia	102,4	44,2	342,5	215,8	704,9	7,61
Volyn	31,2	14,8	108,4	64,5	218,9	2,36
Dnipropetrovsk	68,5	61,4	284,1	142,3	556,3	6,01
Donetsk	12,4	10,8	45,2	22,1	90,5	0,98
Zhytomyr	52,1	25,6	194,3	112,4	384,4	4,15
Zakarpattia	9,8	2,1	24,6	18,5	55,0	0,59
Zaporizhzhia	24,1	30,5	112,4	54,6	221,6	2,39
Ivano-Frankivsk	28,4	12,3	92,1	58,4	191,2	2,06
Kyiv	94,6	32,4	310,2	198,7	635,9	6,87
Kirovohrad	81,2	68,4	315,6	165,4	630,6	6,81
Luhansk	4,1	5,2	16,4	8,2	33,9	0,37
Lviv	45,6	21,5	154,2	96,5	317,8	3,43
Mykolaiv	48,2	52,3	210,5	105,2	416,2	4,49
Odessa	74,3	64,1	302,4	148,6	589,4	6,36
Poltava	114,2	48,6	365,4	232,1	760,3	8,21
Rivne	36,5	15,2	120,3	72,4	244,4	2,64
Sumy	76,4	34,1	248,5	146,2	505,2	5,46
Ternopil	78,5	26,4	234,1	152,4	491,4	5,31
Kharkiv	62,3	46,2	225,4	124,1	458,0	4,95
Kherson	14,2	16,5	62,4	30,2	123,3	1,33
Khmelnyskyi	96,8	34,7	298,7	194,5	624,7	6,75
Cherkasy	92,4	36,8	288,4	185,2	602,8	6,51
Chernivtsi	18,5	5,4	54,2	34,6	112,7	1,22
Chernihiv	91,2	32,1	294,6	178,4	596,3	6,44
TOTAL	1347,4	741,1	4462,4	2712,3	9263,2	100,00

Source: based on the Bioenergy Association of Ukraine (2025).

The national raw material balance demonstrates a dominance of solid biofuels, which account for the lion's share of the total volume (48.2%), confirming the priority and high financial efficiency of using by-products of crop production, in particular, straw of grain crops and sunflower residues, for the direct replacement of fossil fuels. The second-largest structural element is biogas, the generation of which is closely linked to the infrastructure of large livestock complexes and food industry enterprises, which act as logistical hubs to minimise the costs of biomass collection.

Analysis of the geographical distribution of potential shows that Ukraine's key industrial clusters are the Poltava, Vinnitsia, and Kirovohrad regions, which together account for almost a quarter of the country's total energy potential. The Poltava and Vinnitsia regions achieved the highest performance owing to the synergistic combination of powerful corn and wheat residues with high-energy associated wastes of the beet sugar complex, such as molasses and pulp and livestock waste.

At the same time, the Kirovohrad region maintained its leading position, mainly due to the significant volumes of sunflower husks and stalks, which are a financially profitable resource for pelleting and briquetting. In contrast to the central regions, the Northern and Western macroregions demonstrate a more moderate density of bioenergy resources, and the lowest raw material potential is recorded in Chernivtsi and Zakarpattia regions, which is directly due to their natural and geographical features and the structure of agricultural production. The full practical implementation of this spatially differentiated potential can provide significant import substitution for traditional fuel and energy resources, enabling the replacement of substantial volumes of natural gas, thermal coal, and petroleum products in local heat and electricity supply systems and in the state's transport sector. Despite the significant raw material potential of Ukrainian fields and farms, the path from corn residues or manure to usable kilowatts of energy remains difficult due to several hidden stumbling blocks.

To turn these challenges into effective solutions, all obstacles and steps to overcome them were combined into a balanced system (Table 6).

The implementation of recommendations will enable the transformation of the Ukrainian agricultural sector into one that ensures stable heat and electricity supplies for regions.

Table 6. Barrier–Strategy Matrix for Bioenergy Development in Agriculture.

Category	Key Barriers	Strategic Recommendations
Economic and financial	The shortage of available “long” loans for the construction of stations, the high cost of equipment, and the long payback period of projects under current conditions.	Introduction of preferential state lending, attraction of international “green” grants and creation of guarantee funds to protect investments.
Legislative and regulatory	Bureaucratic complexity of connecting biogas plants to electricity and gas networks, as well as the lack of clear rules for long-term export of biomethane to the EU.	Maximum simplification of permitting procedures, launch of a transparent biomethane market, and harmonization of Ukrainian environmental certificates with European standards.
Technical and logistical	Instability of the chemical composition of raw materials by season, high costs of harvesting and transporting biomass, and lack of specialized equipment.	Transition of agricultural enterprises to co-fermentation (joint fermentation), creation of regional logistics hubs for fuel storage and development of biomethane pipeline networks.

5. Discussion.

5.1 Agro-Industrial Waste Potential for Energy Decentralisation in Ukraine.

Ukraine’s agro-industrial complex has a powerful renewable resource base capable of serving as one of the cornerstones of post-war energy decentralisation and decarbonisation of the economy. Integrated assessment of the technical and energy potential of biomass at 4.63 million tons of oil equivalent (toe) is consistent with the fundamental conclusions of leading domestic and European institutions. In particular, the dominance of solid biofuels (48.2% in the overall structure) correlates with the high economic and financial efficiency of attracting crop by-products to directly replace coal and natural gas in local heating systems (Kaletnik et al., 2021).

The regional differentiation of the agro-energy potential identified in this study deserves special attention. The concentration of key resources in the Poltava, Vinnytsia, and Kirovohrad regions indicates the feasibility of forming inter-sectoral bioenergy clusters in the Central macroregion. The high density of corn and sunflower crop residues is combined with a well-developed food industry and livestock infrastructure (Skoutida et al., 2024).

This approach confirms the proposed hypotheses (Hontaruk et al., 2024) regarding the critical role of beet sugar and alcohol enterprises in generating biogas and digestate. Concentrating waste (pulp, molasses, and bran) at industrial sites minimises logistical costs, making these regions the primary drivers of investment growth.

Unlike many optimistic estimates of theoretical potential, the model presented in this study is more restrained and pragmatic. It is based on environmental constraints (preserving the humus balance by removing no more than 25–30% of straw) and logistical accessibility (considering only the large-scale sector of enterprises). Such an adjustment to the methodology is considered critically important because, as our calculations demonstrate using the example of fodder crops and waste from the private livestock sector, the high dispersion of raw materials within households makes their industrial collection economically impractical.

However, the transition of the Ukrainian agro-industrial complex to closed circular economy cycles is hampered by a complex of interconnected barriers. The economic shortage of long-term investment capital, combined with the technical instability of biomass and bureaucratic obstacles to connecting to energy networks, creates high risks for businesses.

Overcoming these challenges requires not only targeted subsidies but also a systemic transformation of state regulation, from harmonising environmental certificates with the requirements of the European Green Deal to developing regional logistics hubs and digital platforms for managing raw material flows.

Promising areas of further scientific exploration in the context of the outlined issues are modelling the dynamics of energy potential, considering climate change and transformation of the structure of sown areas, as well as a detailed analysis of the economic efficiency of co-fermentation of various types of substrates to maximise biomethane yield in the conditions of specific regional clusters.

5.2. Limitations.

The study of the spatially differentiated potential for biofuel production in Ukraine in 2025 has several methodological and geopolitical limitations, which should be considered when using the results in practice.

The regional structure developed in this study is based on the State Statistics Service of Ukraine, which reflects the real state of the agricultural sector in government-controlled territories. Accordingly, the calculations do not consider the theoretical potential of biomass from temporarily occupied territories, territories where active hostilities are underway, or territories with significant landmines, as full-fledged agricultural production and the logistical collection of by-products are currently technically impossible there.

The potential assessment was calculated for average agro-climatic conditions in 2025, and the basic trends in yield and sown areas of previous periods were extrapolated. The applied methodology cannot fully predict or eliminate the impact of force majeure weather anomalies. Extreme droughts, prolonged rains during harvest, and anomalous temperature fluctuations can locally or nationwide alter the gross crop harvest and, consequently, the volume of available plant residues. The forecast indicators formed are an optimised potential model under conditions of relative stability of current agro-production factors and require flexible adjustment in the event of the deoccupation of territories or significant climate change.

6. Conclusions.

A comprehensive assessment of the technical and energy potential of biomass in Ukraine's agricultural sector was conducted, and its strategic role in ensuring energy decentralisation and the energy independence was substantiated. Analysis of the formation of the raw material base has revealed a high spatial concentration of agro-energy resources. The key areas for biomass generation are Poltava, Vinnytsia and Kirovohrad regions. The waste structure is clearly dominated by crop by-products (corn residues, sunflower, and grain straw). It has been established that the most promising locations for the deployment of industrial biogas capacities are food industry enterprises (sugar and alcohol plants), where large, homogeneous volumes of raw materials (pulp, molasses, and pomace) are concentrated, thereby minimising logistics costs.

The application of the developed mathematical model enabled a pragmatic, environmentally safe assessment of the integral technical and energy potential of biomass in Ukraine, amounting to 4.63 million toe. Unlike existing theoretical approaches, the model, for the first time, considered a strict agro-ecological criterion (removal of no more than 25–30% of plant residues to preserve the humus balance) and the institutional barrier to large-scale commercialisation (screening out dispersed livestock waste in private households). In the available potential structure, 48.2% falls under solid biofuels, confirming their priority for primary commercialisation.

It has been proven that the effective use of the calculated potential of agrobiomass can provide a significant replacement for scarce fossil fuels, primarily natural gas and coal, in local heat and power supply systems.

The transformation of organic waste from large-scale complexes into biomethane and digestate (organic fertilisers) creates a closed production cycle that not only strengthens energy security in martial law conditions but also drives the decarbonisation of the industry.

It has been identified that a lack of long-term investment capital hampers the transition of the Ukrainian agricultural industry to circular bioeconomy models.

Regulatory obstacles to the integration of biomethane into gas transportation networks, and instability in raw material supply chains.

To overcome these barriers, a set of tools has been proposed, including the digitalisation of raw material flows management, the development of regional logistics hubs, and the harmonisation of national environmental certificates with EU standards. The accumulation of intellectual capital and the digitalisation of enterprises are the fundamental basis for the industry's flexible adaptation to the conditions of the digital economy.

The practical significance of the results lies in the development of applied tools for state bodies and business entities to formulate post-war energy decentralisation strategies and regional programmes for renewable energy development, aimed at increasing the global competitiveness of domestic agribusiness.

Conflict of Interest Statement.

The authors declare no conflict of interest.

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AI Use Statement.

The authors used Grammarly to improve language clarity and readability. The authors reviewed and edited the output and take full responsibility for the content of the article.

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