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RESEARCH ARTICLE

Circular Bioeconomy in Russian Agriculture: Conceptual Foundations and Regional Implementation Models

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ABSTRACT

Introduction. The transition to sustainable models of natural resource management has become a key priority of agricultural policy in the world's leading economies. In the Russian agricultural sector, a substantial gap remains between the available resource potential of agricultural biomass and its actual utilization in economic activities. The concept of a circular bioeconomy, based on the closed-loop use of organic resources, remains insufficiently developed with regard to the regional specificities of Russia. The aim of this study is to develop the conceptual foundations of a circular bioeconomy in Russian agriculture and to substantiate regional models for its implementation. Materials and Methods. The study focuses on five key agricultural regions of Russia: Krasnodar Krai, Rostov Oblast, Belgorod Oblast, the Republic of Tatarstan, and Voronezh Oblast. The information base includes data from the Federal State Statistics Service (Rosstat), the Ministry of Agriculture of the Russian Federation, and regional authorities for the period 2022–2025. The study employs methods of comparative regional analysis, systematization of bioeconomic indicators, and forecast extrapolation of time series data. Results. A system of regional bioeconomic indicators was developed, including agricultural biomass volumes, agricultural waste generation, waste processing rates, and biogas production potential. Belgorod Oblast was found to possess the highest biogas generation potential, reaching 3.9 billion cubic meters by 2025. A generally positive trend was identified: the share of processed agricultural waste in the studied regions is projected to increase by 5–9 percentage points between the baseline period and 2025. Differentiated regional models for implementing circular bioeconomy principles were proposed, taking into account the sectoral structure of each region. Discussion and Conclusions. The findings indicate the existence of significant yet underutilized potential for the development of a circular bioeconomy in Russian agriculture. The practical significance of the study lies in the possibility of applying the proposed models in the development of regional agricultural policy and strategic planning. Future research should focus on the development of government support mechanisms and the assessment of the economic efficiency of bioeconomy projects across different agricultural sectors.

INTRODUCTION

The global transition toward sustainable production and consumption models has stimulated the rapid development of the bioeconomy concept, which involves the use of biological resources, biotechnologies, and biological processes to create economic value while minimizing environmental impacts. A central element of this paradigm is the circular bioeconomy, an approach that integrates the principles of the circular economy with bioeconomic mechanisms and seeks to maximize the value of biological resources throughout their life cycle.Agriculture is a key sector for the implementation of circular bioeconomy principles. Russia possesses approximately 10% of the world's agricultural land, generates more than 800 million tonnes of agricultural biomass annually, and produces over 300 million tonnes of organic waste. At the same time, a substantial share of this bioresource potential remains underutilized due to fragmented public policies, insufficient development of biotechnology infrastructure, and the absence of systematic regional implementation mechanisms.

The relevance of this study stems from several factors: the need to ensure national food security under economic sanctions; the need for agriculture to contribute to Russia's national goal of achieving carbon neutrality no later than 2060; and the strategic priorities established by the Strategy for the Development of the Agricultural and Fisheries Sectors of the Russian Federation through 2030. In addition, the need to replace imported biotechnological components makes the development of a domestic circular bioeconomy system a national priority.

Russian researchers primarily consider the bioeconomy as an innovative driver of agricultural development. They emphasize its role in improving the competitiveness of the agricultural sector, although often without considering regional differences in institutional conditions. Other studies examine challenges associated with the development of the bioeconomy in Russian regions, highlighting deficiencies in infrastructure, while research on green agricultural development generally lacks an operational classification of regional implementation models. International studies, including those by Schütte [OECD, 2018; Schütte, 2018], propose universal conceptual frameworks for the circular bioeconomy but do not account for the institutional specificities of Russian agriculture. Consequently, the scientific literature lacks a systematic classification of regional circular bioeconomy models applicable to Russian agriculture, which constitutes the research gap addressed in this study.

The research hypothesis is that the effectiveness of the transition to a circular bioeconomy in agriculture depends on the type of regional model developed in accordance with the sectoral specialization and resource potential of a constituent entity of the Russian Federation.

The aim of this study is to develop a mechanism for implementing the circular bioeconomy in Russian regions and to classify regional circular bioeconomy models in Russia. To achieve this objective, the following tasks are addressed: systematization of theoretical approaches to the circular bioeconomy; analysis of the bioresource potential of key Russian regions; classification and justification of regional models; and development of practical recommendations.

MATERIALS AND METHODS

The study examines agriculture in five key Russian regions: Krasnodar Krai, Rostov Oblast, Belgorod Oblast, the Republic of Tatarstan, and Voronezh Oblast. These regions were selected because they account for more than 28% of the country's agricultural output and have substantial bioresource potential.

The study draws on data from the Federal State Statistics Service (Rosstat) on agriculture, hunting, and forestry (2022–2025); harvest progress reports issued by the Ministry of Agriculture of the Russian Federation (2023–2025); analytical reports of the Russian Biofuel Union on the biogas sector in Russia; materials published by the Federal State Budgetary Scientific Institution "Rosinformagrotekh"; and regional agricultural development programs and organic farming strategies.

The research methodology includes

1. A systematic review and critical analysis of Russian and international literature on the bioeconomy and circular economy;
2. A comparative regional analysis of bioeconomic indicators for 2022–2025 (with 2025 represented by preliminary data);
3. A classification method used to develop a typology of regional models based on sectoral specialization, volumes of biomass streams, and the level of institutional development;
4. A linear trend extrapolation method used to forecast indicators for 2025 in each analyzed region. Forecast values were obtained by extending the average annual growth rate of the base period (2022–2024), taking into account the planned targets of regional development programs available at the time of writing.

The study covers the period 2022–2024, with forecasts extending through 2025. The geographical scope includes the Southern, Central, and Volga Federal Districts of the Russian Federation.

RESULTS

1: Conceptual Foundations of the Circular Bioeconomy

Under current conditions of economic sanctions and import-substitution policies, the development of the production potential of Russian agriculture plays an important role both in agricultural production and in the processing of agricultural raw materials. This importance reflects the lengthy production cycles in crop farming, agriculture's strong dependence on natural and climatic conditions, and the challenges associated with livestock production [Udalov, 2019, p. 375].

The concept of the "bioeconomy" entered scientific discourse in the early 2000s and has undergone significant evolution, from a narrow sectoral interpretation as a synonym for the biotechnology sector to a broader systemic approach encompassing all aspects of the production, processing, and consumption of biological resources. A key document that established the modern understanding of the concept was the 2018 EU Bioeconomy Strategy, which defined the bioeconomy as "the production of renewable biological resources and the conversion of these resources and waste streams into value-added products, such as food, feed, bio-based products and bioenergy" [*European Commission, 2018*].

An important current priority is the development of standards for green products as part of an integrated agricultural system. The adoption of such standards represents a significant step toward reducing the negative impacts of production and consumption on the environment, climate, natural resources, and human health [Udalov and Udalova, 2020, p. 65].

The circular bioeconomy emerges at the intersection of two concepts—the "green bioeconomy" and the "circular economy"— and is based on four fundamental principles [Schütte, 2018]:

1. Cascading use of biomass — the sequential extraction of maximum value from each biomass stream (food, feed, chemical feedstocks, and energy);
2. Closed nutrient cycles — the return of nutrients to ecosystems through composting, anaerobic digestion, and soil biofortification;
3. Biotechnological transformation — the application of fermentation technologies, enzymology, and synthetic biology to enhance bioavailability and resource efficiency;
4. Systemic integration of stakeholders and processes — the establishment of territorial bioclusters that integrate agricultural production, bioprocessing, research, and public administration.

The fundamental difference between the circular bioeconomy and the linear model of "production–consumption–disposal" lies in the systematic reconceptualization of waste as a resource and the creation of closed-loop bioeconomic systems. A comparative analysis of these models as applied to agriculture is presented in Table 1.

Table 1: Comparison of Linear and Circular Models in Agriculture

Criterion	Linear Model	Circular Bioeconomy
Waste management	Landfilling or incineration, with losses exceeding 60%	Resource recovery and cascading use
Biomass use	Single-purpose use, such as feed or energy	Multipurpose use: food, feed, biochemicals, and energy
Nutrient retention	Nutrients are lost through landfilling	Nutrients are retained through biogas digestate and compost
Application of biotechnology	Limited and isolated	System-wide application at all stages of the value chain
Carbon footprint	High, due to CH_4 and N_2O emissions from waste	Reduced by 30–45% through closed-loop cycles
Economic efficiency	Low value added	Two- to threefold increase in the value added of bioresources
Cross-sectoral integration	Weak	Systemic integration through bioclusters and agro-industrial parks
Institutional framework	Sector-specific regulatory bodies	Cross-sectoral bioeconomy strategies

Comparative analysis shows that the linear model of agricultural production has exhausted its potential for economic efficiency: more than 60% of biological resources are irretrievably lost at the waste management stage, while weak cross-sectoral integration limits value creation. The circular bioeconomy offers a systemic alternative based on the cascading use of biomass, with value extracted sequentially at each stage of the chain: food, feed, biochemicals, and energy. Importantly, the transition to a circular model generates not only environmental benefits, including a 30–45% reduction in CH_4 and N_2O emissions, but also measurable economic gains, as the value added of biological resources increases two- to threefold. Realizing this potential requires a shift in institutional logic from sector-specific regulation to cross-sectoral bioeconomy strategies that integrate participants in agricultural clusters across all stages of the value chain.

2: Bioresource Potential of Agriculture in Key Russian Regions

Russia has one of the world's largest bioresource bases for the development of a circular bioeconomy, including 116 million hectares of arable land, 70 million hectares of natural pasture, and 800 million hectares of forest land. However, the utilization of this potential varies considerably across regions due to differences in natural and climatic conditions, sectoral specialization, and institutional development. Analysis of statistical data from Rosstat, the Ministry of Agriculture of the Russian Federation, and regional reports for 2022–2024 identified five leading regions in terms of agricultural bioresource potential. Their bioeconomic indicators are presented in Table 2.

Table 2: Bioeconomic Indicators of Key Agricultural Regions in Russia (2022–2025)

Region	Indicator	2022–2023 (Baseline)	2024 (Actual)	2025 (Forecast)	Change from Baseline to 2024
Krasnodar Krai	Arable land, million ha	3,9	4,0	4,0	+2,6%
	Agricultural biomass, million t/year	48,2	51,4	53,8	+6,6%
	Agricultural waste, million t/year	12,4	13,2	13,9	+6,5%
	Share of waste processed, %	18	21	24	+3 pp
	Biogas potential, billion m^3	2,3	2,6	2,9	+13,0%
Rostov Oblast	Arable land, million ha	5,5	5,7	5,7	+3,6%
	Agricultural biomass, million t/year	32,7	35,1	36,9	+7,3%
	Agricultural waste, million t/year	9,1	9,8	10,4	+7,7%
	Share of waste processed, %	12	14	17	+2 pp
	Biogas potential, billion m^3	1,7	1,9	2,1	+11,8%
Belgorod Oblast	Arable land, million ha	1,6	1,6	1,6	0%
	Agricultural biomass, million t/year	18,9	21,3	22,5	+12,7%
	Agricultural waste, million t/year	14,3	15,7	16,2	+9,8%
	Share of waste processed, %	27	31	36	+4 pp
	Biogas potential, billion m^3	3,1	3,5	3,9	+12,9%
Republic of Tatarstan	Arable land, million ha	2,8	2,9	3,0	+3,6%
	Agricultural biomass, million t/year	22,5	24,8	26,2	+10,2%
	Agricultural waste, million t/year	8,6	9,2	9,8	+7,0%
	Share of waste processed, %	21	24	28	+3 pp
	Biogas potential, billion m^3	2,0	2,3	2,5	+15,0%
Voronezh Oblast	Arable land, million ha	3,2	3,3	3,4	+3,1%
	Agricultural biomass, million t/year	25,1	27,4	29,0	+9,2%
	Agricultural waste, million t/year	7,8	8,5	9,0	+9,0%
	Share of waste processed, %	14	17	20	+3 pp
	Biogas potential, billion m^3	1,5	1,8	2,0	+20,0%

Source: [Rosstat: Agriculture, Hunting, and Forestry, 2026]

Krasnodar Krai. In 2024, agricultural biomass output reached 51.4 million t/year, an increase of 6.6% from the baseline period, due to the expansion of irrigated land under Resolution No. 1567-r of the Government of the Russian Federation (2022) and higher grain yields. The share of agricultural waste processed increased from 18% to 21% following the commissioning of two biogas plants with a combined capacity of 4.8 MW in the Timashevsky and Korenovsky districts. These values exceed the average for the Southern Federal District (14–19%), reflecting the region's higher concentration of processing capacity.

Rostov Oblast. The region has the largest area of arable land at 5.7 million ha, an increase of 3.6%. Agricultural biomass output reached 35.1 million t/year, while the share of agricultural waste processed remained low at 14%, indicating substantial untapped bioeconomic potential. The main constraint is the lack of infrastructure for collecting dispersed plant biomass. The projected biogas potential for 2025 is 2.1 billion m^3.

Belgorod Oblast. The highest share of agricultural waste processing in the sample was recorded at 31%, an increase of 4 percentage points, supported by the biogas cluster operated by API, which includes three plants with a combined capacity of 10.5 MW, and by implementation of the regional Concept for Organic Agriculture through 2030 under Resolution No. 247-pp of 2021. For comparison, the average for the Central Federal District in 2021 was 22–25%, confirming the region's faster rate of development.

Republic of Tatarstan. The largest relative increase in biogas potential was recorded at 15.0%, from 2.0 to 2.3 billion m^3, due to the expansion of the Laishevskaya biogas plant and an 8.4% increase in cattle numbers. The share of agricultural waste processed reached 24%, up 3 percentage points, and is projected to reach 28% in 2025.

Voronezh Oblast. The largest relative increase in biogas potential in the sample, 20.0%, from 1.5 to 1.8 billion m^3, resulted from implementation of an investment agreement with EkoNivaAgro LLC to establish an agricultural biotechnology park in the Anninsky District in 2023–2025. The share of agricultural waste processed increased from 14% to 17%, but remained below the sample average.

Belgorod Oblast, which leads in the processing of organic livestock waste at 27%, has developed the most mature foundation for an agro-energy model of the circular bioeconomy. Krasnodar Krai, due to its leading crop production potential, is the priority region for developing an agricultural bioprocessing cluster [Federal State Statistics Service [Rosstat], 2026].

Overall, the Southern Federal District plays a major role in ensuring the food security of the Russian Federation. Agriculture in the Southern Federal District also occupies an important position in the Russian economy [Udalov and Kabanenko, 2019, p. 207].

3: Classification of Regional Circular Bioeconomy Models in Russian Agriculture.

Based on an analysis of regional bioresource potential, sectoral specialization, and institutional conditions, the authors propose a classification of regional circular bioeconomy models in Russian agriculture comprising three basic types.

1. Agro-Biorefinery Model

This model is intended for regions with high levels of crop production and a well-developed processing industry, including Krasnodar Krai, Rostov Oblast, and Voronezh Oblast. Its key mechanism is biorefining, involving the sequential multipurpose use of plant biomass to produce food, biochemicals, biopolymers, and bioenergy. By-products from sugar production, including beet pulp and molasses, grain processing, including bran and husks, and the vegetable oil industry, including oil cake and meal, form closed-loop biomass streams and can generate up to 35% additional value added [Order of the Government of the Russian Federation No. 2567, 2022].

2. Agro-Energy Model

This model is designed for regions with a high concentration of livestock enterprises and substantial volumes of organic waste, including Belgorod Oblast and the Republic of Tatarstan. It is based on the anaerobic digestion of livestock manure and poultry litter to produce biogas and biofertilizers. The potential of Belgorod Oblast alone is estimated at 3.1 billion m^3 of biogas per year, equivalent to 18.6 PJ of thermal energy. Returning digestate to the soil closes the nutrient cycle and reduces the need for mineral fertilizers by 25–30% [Paptsov, 2019].

3. Biocluster Model

This model is applicable to regions with diversified agricultural systems, developed research infrastructure, and strong innovation potential, including the Republic of Tatarstan, Moscow Oblast, and Novosibirsk Oblast. It involves the establishment of territorial bioeconomy clusters that bring together agricultural producers, bioprocessing enterprises, research centers, biotechnology companies, and development agencies. Cluster-based organization creates synergies through shared infrastructure, technology transfer, and the integration of biomass streams [Glazyev SYu. (2018)]. The comparative characteristics of the three models, including their target indicators and key implementation risks, are summarized in Table 3.

Table 3: Typology of Regional Circular Bioeconomy Models in Russian Agriculture

Parameter	Agro-Biorefinery Model	Agro-Energy Model	Biocluster Model
Target regions	Krasnodar Krai, Rostov Oblast, Voronezh Oblast	Belgorod Oblast, Republic of Tatarstan	Republic of Tatarstan, Moscow Oblast, Novosibirsk Oblast
Primary biomass stream	Plant biomass and crop production waste	Manure and poultry litter from livestock enterprises	Diversified biomass streams
Key technologies	Biorefining, fermentation, biopolymers	Anaerobic digestion, biogas production, composting	Synthetic biology, platform biotechnologies
Target indicators (5 years)	35% reduction in biomass losses; 2.5-fold increase in value added	Biogas production of at least 2 billion m^3/year; 40% reduction in CH_4 emissions	Establishment of at least three bioclusters; 60% increase in patent activity
Key risks	Unstable raw material supply; low profitability of biochemical production	High capital investment in biogas plants	Shortage of qualified personnel; long payback period
Required support measures	Subsidies for biorefinery equipment; tax incentives	Concessional loans for biogas plants; green tariffs	R&D funding; special economic zones for biotechnology
Expected economic effect	18–25% increase in the revenue of processing enterprises	Fertilizer cost savings of RUB 3,000–5,000/ha; revenue from bioenergy sales	Multiplier effect: RUB 1 generates RUB 3–4 in GRP

Source: Compiled by the authors based on [Glazyev, 2018; Paptsov, 2019; Strategy for the Development of the Agricultural and Fisheries Sectors through 2030, 2022)].

The proposed regional circular bioeconomy models reflect a differentiated approach to managing the bioresource potential of agriculture: the choice of model depends on the structure of dominant biomass streams, the region's technological maturity, and its investment capacity.

The agro-biorefinery model is intended for regions with highly concentrated crop production and seeks to maximize value added through biorefining and advanced biomass processing. The agro-energy model is most effective in regions with a high density of livestock enterprises: anaerobic digestion simultaneously addresses environmental goals by reducing CH_4 emissions by 40% and energy goals by producing at least 2 billion m^3 of biogas per year. The biocluster model provides the greatest multiplier effect, with RUB 1 generating RUB 3–4 in gross regional product, but requires well-developed innovation infrastructure and a long-term planning horizon.

A common limitation of all three models is institutional fragmentation. Effective implementation is possible only with comprehensive government support, including subsidies, green tariffs, and targeted R&D funding. Without systematic support measures, market incentives are insufficient to overcome the high entry barriers associated with bioeconomy projects.

4: Mechanisms for Implementing the Circular Bioeconomy in Russian Agriculture

The implementation of regional circular bioeconomy models requires a comprehensive mechanism combining government regulation, market incentives, technological infrastructure, and institutional conditions. The authors' concept of this mechanism is presented in Figure 1

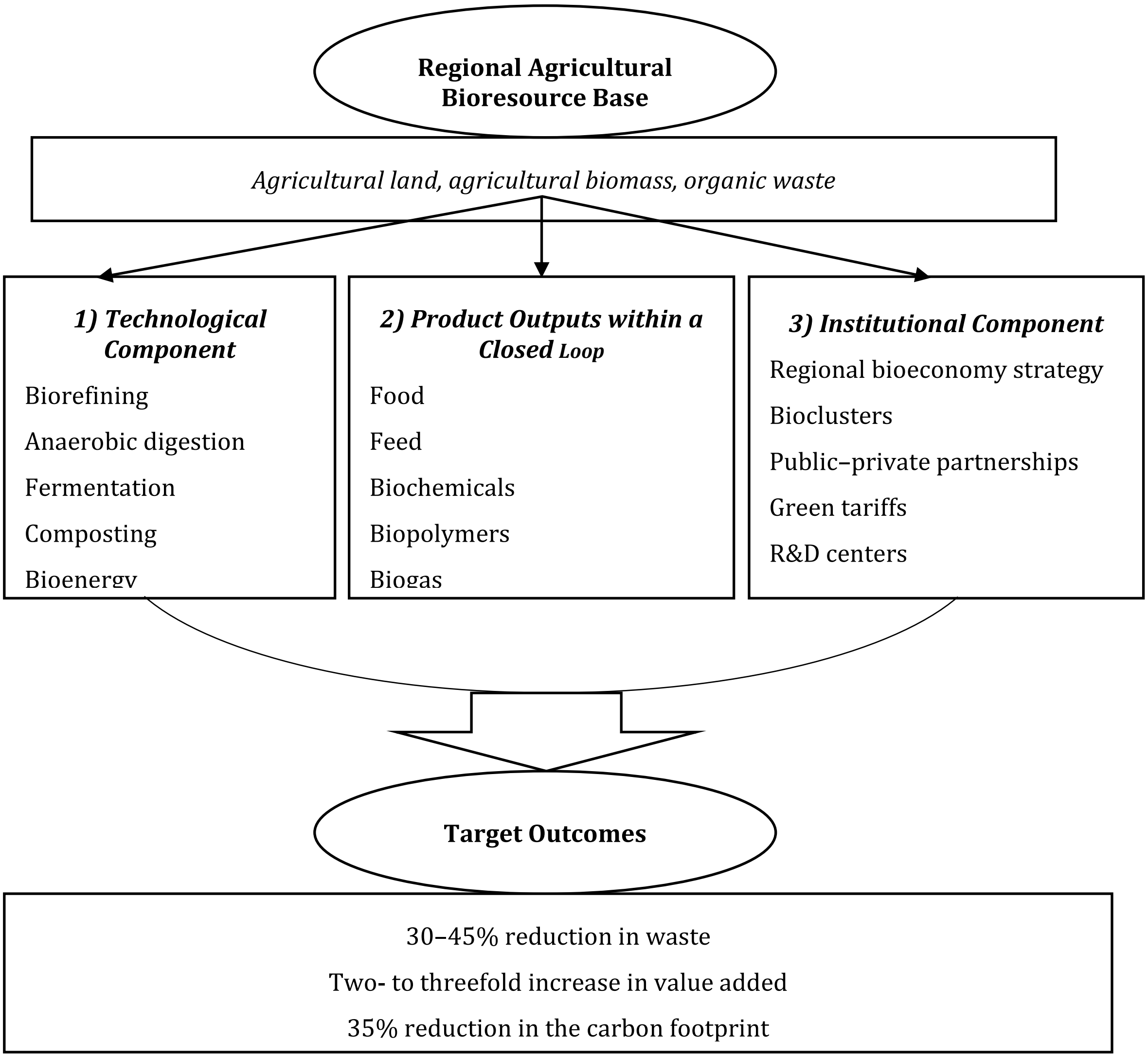

Figure 1: Mechanism for Implementing the Circular Bioeconomy in Regional Agriculture[1]

The implementation mechanism comprises three interrelated components. The technological component includes biorefining, anaerobic digestion, fermentation, composting, and bioenergy. The closed-loop product component includes food, feed, biochemicals, biopolymers, biogas, and biofertilizers returned to agricultural production. The institutional component includes regional bioeconomy strategies, bioclusters, public–private partnerships, green tariffs, and R&D centers [Glazyev 2018; Paptsov, 2019].

Experience shows that pilot projects implemented within agro-industrial parks are the most effective instrument for launching the circular bioeconomy in the regions. In 2022, the 3.6 MW Luchki biogas complex, operated by Agriconsult Group LLC, was commissioned in Belgorod Oblast. The facility processes 75,000 tonnes of manure annually and produces 18,500 tonnes of biofertilizers, providing a clear example of a closed-loop agricultural bioenergy cycle. The Republic of Tatarstan is implementing a program for the development of agricultural biotechnology parks within the Kama cluster. By 2024, the share of organic agricultural waste processed in the republic had reached 31%, substantially exceeding the national average.

DISCUSSION AND CONCLUSIONS

The findings make it possible to formulate several points for discussion that are relevant to the advancement of knowledge in this field.

The proposed classification of three regional models – the agro-biorefinery, agro-energy, and biocluster models-develops the approach of international researchers who distinguish types of circular bioeconomy systems without linking them to the sectoral characteristics of agricultural production. Unlike the universal EU typologies [*European Commission, 2018*], the proposed classification accounts for the institutional environment and sectoral structure of Russian regions, making it directly applicable to regional policymaking.

The recorded variation in the share of agricultural waste processed, ranging from 12% to 27% during the baseline period, is substantially below the corresponding levels in leading EU regions, which ranged from 40% to 65% according to Eurostat data for 2022. This confirms the conclusions of Russian researchers regarding the systemic lag of Russian agriculture in bioeconomic transformation. At the same time, the rapid improvement observed in Belgorod Oblast, with an increase of 4 percentage points in one year, demonstrate that the 2030 targets are achievable, provided that systematic government support is available.

The limitations of the study are associated with restricted access to primary data at the level of individual enterprises, which prevents verification of forecast values at the micro level. In addition, forecasting by trend extrapolation may underestimate the nonlinear effects of technological breakthroughs or institutional changes. These limitations define priorities for future research.

The practical significance of the findings lies in their potential use in developing regional bioeconomy strategies for constituent entities of the Russian Federation with different agricultural specializations, as well as in formulating federal support measures for biotechnology infrastructure.

The study yielded the following main conclusions.

First, the circular bioeconomy provides an effective conceptual foundation for transforming Russian agriculture toward sustainable development by creating synergies among economic efficiency, environmental responsibility, and food security.

Second, substantial regional differences in Russia's bioresource potential necessitate a differentiated approach to implementing the circular bioeconomy. The proposed classification of three basic regional models makes it possible to adapt bioeconomy policy instruments to the specific characteristics of each region and confirms the research hypothesis.

Third, the key conditions for successful implementation include the development of regional bioeconomy strategies as part of agricultural development programs, the creation of specialized biotechnology infrastructure, the establishment of targeted financial support mechanisms, and the training of specialists in the bioeconomy.

Fourth, the implementation of regional circular bioeconomy models can reduce agricultural waste by 30–45%, increase the value added of biological resources two- to threefold, and reduce greenhouse gas emissions by 35%, which is consistent with the targets of the Strategy for the Development of Agriculture of the Russian Federation through 2030.

Future research should focus on developing quantitative methods for assessing regional bioeconomy potential, analyzing financial mechanisms for circular bioeconomy projects within the Russian institutional environment, and monitoring the effectiveness of pilot projects at the enterprise level.

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