Research Article

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Biogas as a Strategic Resource: Analysis of the Potential and Mechanisms for Managing Poultry Waste in Kazakhstan

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Abstract

Biogas technologies play a key role in the development of sustainable energy, especially in agricultural countries with high volumes of organic waste. In the context of increasing climate and environmental challenges, the development of the biogas sector is becoming especially relevant to ensure energy security and reduce the burden on the environment. The purpose of the article is to identify the potential of using poultry manure as a feedstock for biogas production in Kazakhstan. An analysis of the efficiency of biogas plants is conducted based on statistical data on biomass volumes from poultry farms, agricultural enterprises, and household sources. The study describes the environmental and economic benefits of adopting biogas technologies, including the reduction of greenhouse gas emissions and lower energy costs. Additionally, technical challenges and barriers to the widespread implementation of biogas systems are explored, such as high capital costs and the need for personnel training. Projections for 2025-2029 indicate steady growth in biogas production volumes, supported by government policies and the expansion of technological infrastructure. The article provides recommendations for enhancing the efficiency of biogas projects and improving the environmental situation in agricultural regions of Kazakhstan.

Keywords: *biogas, poultry manure, renewable energy, agriculture, environmental benefits, economic efficiency*

1. Introduction

Modern environmental and energy challenges increase the need to find sustainable solutions in the agricultural sector, especially in countries such as Kazakhstan, where a resource-based economy traditionally prevails. One of the promising areas is the development of biogas production based on the processing of organic waste, including poultry manure. This technology allows for the simultaneous solution of waste disposal problems, reduction of greenhouse gas emissions and provision of agricultural enterprises with alternative energy sources.

Issues of support and regulation of biogas plants are enshrined in a number of strategic and regulatory documents. Thus, the Strategy for Achieving Carbon Neutrality by 2060 (2023) provides for the reduction of greenhouse gas emissions and the promotion of renewable energy sources, including biogas. The Law of the Republic of Kazakhstan "On Support for the Use of Renewable Energy Sources" (2009) regulates issues of tariff support and incentive mechanisms for renewable energy sources (Yessengeldin et al, 2018), and the Law "On State Regulation of the Production and Circulation of Biofuels" (2010) covers the specifics of the circulation of biogas products. In addition, the Environmental Code of the Republic of Kazakhstan (2021) prioritizes the processing of biodegradable waste and encourages the reduction of its disposal, including through utilization for the purpose of obtaining biogas. The implementation of the provisions of the Concept of Transition to a "Green Economy" (2013) serves as the basis for the institutional promotion of biogas projects. Of particular importance is the introduction of "green" financial instruments, such as bonds and loans (Resolution of the Government of the Republic of Kazakhstan, 2021), which can be used to finance environmentally sustainable solutions, including biogas plants. Thus, the development of institutional and financial mechanisms for stimulating biogas production in Kazakhstan, including through the processing of poultry manure, is a promising area of the state environmental and energy policy. Further advancement requires a comprehensive analysis of existing support mechanisms, barriers to their implementation and the possibilities of scaling up successful practices.

2. Methodology

The study is based on statistical data on the number of poultry and the volume of organic waste over the past five years, provided by the Bureau of National Statistics of the Agency for Strategic Planning and Reforms of the Republic of Kazakhstan. The key steps of the methodology are as follows:

Assessment of Raw Material Availability for Biogas Production. Data on poultry populations in Kazakhstan were organized by categories (poultry farms, farm enterprises, household farms) for the period from 2018 to 2022. The number of poultry on poultry farms, farm enterprises, and household farms served as the basis for calculating the volume of available biomass. This step allowed for the identification of key biomass sources and the calculation of the potential volume of biogas that could be produced.

Calculation of Biogas Production Potential. The average biomass value (in kg/day per bird) and the corresponding biogas yield factor (m^3/kg of biomass) were used. These data allowed for the calculation of total biomass and the projected biogas production for different sources (poultry farms, farm enterprises, household farms). As a result, the total daily biogas production in Kazakhstan was obtained, and a forecast for the annual volume was made.

Government Support Tools. An important part of the methodology is the analysis of existing government support tools for the development of biogas installations in Kazakhstan, including auction mechanisms and subsidies for the installation of biogas plants. These data were used to assess the current state of the sector and identify areas that require improvement.

2.1 Evaluation of Biogas Production Efficiency from Poultry Manure Based on a Two-Factor Correlation-Regression Model

To assess the relationship between biomass volume and biogas production, a two-factor correlation-regression model was constructed.

The two-factor correlation-regression model is represented by the following equation:

$$\hat{y}_x = a_0 + a_1 \cdot x \qquad (1)$$

For determining the parameters a_0, and a_1, the following system of linear equations is applied:

$$\begin{cases} a_0 \cdot n + a_1 \cdot \sum x = \sum y \\ a_0 \cdot \sum x + a_1 \cdot \sum x^2 = \sum y \cdot x \end{cases} \quad (2)$$

To determine the reserves in the independent factor, the elasticity coefficient is used, which shows the average change in the dependent variable *y* when the independent factor *x* changes by 1%.

The elasticity coefficient is defined as follows:

$$E = a_1 \cdot \frac{\overline{x}}{\overline{y}} \quad (3)$$

Where:

a_1 is the regression coefficient for the factor *x*;

$\overline{x}$ overline is the mean value of the independent factor,

$\overline{y}$ is the mean value of the dependent variable,

E is the elasticity coefficient, which shows how many percent the dependent variable will change with a 1% change in the independent factor.

The quality of the linear regression model is assessed using several indicators that help determine how well the model fits the data and how accurate the predictions are. The main methods for evaluating the model quality include:

Coefficient of Determination (R^2): This indicator measures the proportion of variance in the dependent variable that is explained by the independent variable. It ranges from 0 to 1:

If $R^2 = 1$, it means the model perfectly predicts the dependent variable.

If $R^2 = 0$, it means the model does not explain the relationship at all.

The higher the R^2 value, the better the model fits the data.

Mean Squared Error (MSE): The mean squared error indicates how much the predicted values deviate from the actual values.

$$MSE = \frac{1}{n} \sum_{i=1}^{n} (y_i - \hat{y}_i) \quad (4)$$

where y_i is the actual value, a $\hat{y}_i$ is the predicted value of the model. The smaller this value, the more accurate the model.

Mean Absolute Error (MAE). MAE shows the average magnitude of the absolute deviations between the predicted values and the actual values:

$$MAE = \frac{1}{n} \sum_{i=1}^{n} |y_i - \hat{y}_i| \quad (5)$$

This gives an understanding of the average error of the model.

To calculate this, a confidence interval for the regression coefficients is used, as well as a confidence interval for the predicted values.

To assess the standard error of the regression coefficients, the residuals of the model (the difference between the actual and predicted values) are used. The confidence interval typically employs a significance level of $\alpha = 0.05$, which corresponds to a 95% confidence interval.

The calculation of the t-statistic: This can be done by using the Student's t-distribution to account for the model's degrees of freedom and the significance level.

The confidence interval for each regression coefficient is calculated using the following formula:

$$\hat{\beta}_i \pm t \cdot SE\left(\hat{\beta}_i\right) \quad (6)$$

Where:

$\hat{\beta}_i$ is the estimated value of the regression coefficient,

t is the quantile from the Student's t-distribution,

$SE(\hat{\beta}_i)$ is the standard error of the regression coefficient $\hat{\beta}_i$

To calculate the confidence interval for predictions, we need to consider both the uncertainty in the estimation of the regression coefficients and the random errors that occur when making predictions based on the data. The standard error of prediction accounts for both the variability of the actual data and the uncertainty in the estimation of the coefficients. The formula for the standard error of prediction is:

$$SE_{(y)} = \sqrt{MSE \cdot (1 + \frac{1}{n} + \frac{(x_{new} - \bar{x})^2}{\sum(x_i - \bar{x})^2}} \qquad (7)$$

Where:

MSE is the Mean Squared Error,

$\bar{x}$ is the mean value of the independent variable.

Based on the constructed regression model, a biogas production forecast was made for the next five years (2025–2029). The forecasted values were supported by the calculation of confidence intervals at a 95% significance level, which allows for accounting for potential data fluctuations and model uncertainties.

Environmental Aspects. The study also analyzed the environmental aspects of using biogas plants. To this end, calculations of greenhouse gas emissions (ammonia, methane, nitrous oxide) from poultry manure were carried out, based on biomass data from different types of farms (poultry farms, farms, household farms). This allowed for the evaluation of each type of farm's contribution to total emissions and the identification of key sources of pollution.

3. Literature Review

The economic benefits of producing biogas from poultry manure have been the subject of active research in recent years. Many scientists emphasize that this technology allows for lower energy costs, improved environmental conditions, and additional income from the use of biofertilizers. A study of the economic efficiency of producing biogas from poultry manure on an industrial scale (Lee, J. et al. (2020) notes that the introduction of biogas plants can significantly reduce energy costs, especially on farms where energy consumption is high. According to their calculations, farmers can save up to 30% on electricity due to biogas production, which significantly increases overall profitability. The authors also emphasize that the production of biofertilizers reduces the cost of purchasing mineral fertilizers.

Atelge, M. R. et al (2020) assessed the economic benefits of processing organic waste, including poultry manure, for biogas production on small farms. They concluded that the main economic benefit lies not only in reducing energy costs, but also in reducing waste disposal costs. In their study, they note that small farms can increase their profitability by 15-20% through the use of biogas plants, especially in regions where the costs of organic waste disposal are high. Technological and economic aspects of using biogas plants in poultry farms were considered in the work of Wang, J., et al. (2023). The study showed that the production of biogas from poultry manure allows not only to generate energy, but also to significantly reduce waste disposal costs. The authors noted that the use of poultry manure as an energy source reduces the need to purchase traditional energy sources, such as gas or electricity from the grid. The economic benefits of such technologies are especially noticeable on large poultry farms, where waste volumes are significant, and annual savings can be up to 25%.

Carrera, R. et al. (2022) assessed the financial and environmental aspects of using poultry manure for biogas production in Latin American farms. They noted that the main advantage of biogas technologies is the reduction in energy costs, as well as the possibility of generating additional income from the sale of biofertilizers. The study found that farms can improve their profitability by 18-22% through the combined use of biogas and biofertilizers, making such plants economically viable for medium and large businesses.

Studying the long-term economic prospects of using biogas plants for processing poultry manure on European farms, Andersen, L., et al. (2018) concluded that investments in such plants pay off in an average of 5-7 years, making them cost-effective for farmers. The authors noted that one of the key factors for economic benefit is the possibility of using biofertilizers, which can either be applied on the farm itself or sold to the market. They emphasized that biogas plants can provide up to 30% savings on energy costs, which contributes to the sustainable development of farms.

Research by various scientists confirms that biogas production from poultry manure is an economically viable solution for farms (Ali et al, 2022; Naidu et al, 2024). The main economic benefits are reduced energy costs, reduced waste disposal costs and the possibility of generating additional income from biofertilizers (Kreidenweis et al, 2020). Combined waste processing methods and improved fermentation technologies can increase the efficiency and profitability of biogas plants. However, the implementation of such technologies requires significant initial investments that pay off in the long term (Zhytar et al, 2025). Technological features of biogas production from poultry manure have a number of key characteristics related to the chemical composition of the manure, the process of anaerobic fermentation, the choice of substrates and the need to use cleaning systems. These features make the process of processing poultry manure into biogas efficient and sustainable, but at the same time require careful monitoring and compliance with technological conditions.

4. Results

4.1 Assessment of Raw Material Availability for Biogas Production from Poultry Manure

According to data from the Bureau of National Statistics of the Agency for Strategic Planning and Reforms of the Republic of Kazakhstan (2023), egg and poultry meat production is distributed as follows: 25.5% in household farms, 1.3% in peasant farms, and 73.2% in large poultry farms (Table 1).

Table 1. Bird Population in Kazakhstan, 2018–2022 million heads

Indicators	2018		2019		2020		2021		2022		Average Quantity	
	m	%	m	%	m	%	m	%	m	%	m	%
Poultry Farms	32.4	73.1	32.8	72.9	30.8	71.1	35.6	74.3	37.3	74.9	33.8	73.2
Farm Households	0.5	1.2	0.6	1.3	0.7	1.6	0.6	0.4	0.6	1.2	0.6	1.3
Household Farms	11.4	25.7	11.6	25.8	11.8	27.3	12.1	25.3	11.9	23.9	11.8	25.5
Total	44.3	100	45.0	100	43.3	100	47.9	100	49.8	100	46.2	100

Over the period of five years, the bird population increased from 44.3 million heads in 2018 to 49.8 million heads in 2022. This indicates an overall positive trend in the growth of the bird population in the country. The average bird population during the analyzed period was 46.2 million heads.

There is a gradual increase in the number of birds on poultry farms, with some fluctuations (e.g., a slight decline in 2020 to 30.8 million heads). By 2022, a consistently high growth rate was observed, reaching 37.3 million heads. On average, over the five years, the bird population on poultry farms amounted to 33.8 million heads, accounting for 73.2% of the total population. This highlights the dominance of poultry farms in Kazakhstan's poultry industry.

The number of birds in agricultural enterprises is relatively small compared to other categories. In 2018, the population was 0.5 million heads (1.2%), and in 2022, it increased slightly to 0.6 million heads (1.2%). The average bird population in agricultural enterprises over the five years was 0.6 million heads, representing 1.3% of the total population. This indicates the minor role of agricultural enterprises in the country's poultry sector.

In 2018, the bird population in households was 11.4 million heads (25.7%). By 2022, the population slightly increased to 11.9 million heads; however, its share of the total population decreased to 23.9%. Despite the relative stability in the bird population in households (averaging about 11.8 million heads over the five years), its percentage share tends to decline. This is attributed to the faster growth of the bird population on poultry farms.

The table demonstrates the dominance of large poultry farms in the structure of Kazakhstan's poultry industry. Their share increased from 73.1% in 2018 to 74.9% in 2022. Despite fluctuations, the overall bird population has been steadily growing, which may be linked to the development of the poultry sector and increasing demand for poultry products.

Large poultry farms remain the most significant polluters of the environment under modern conditions. Currently, 69 poultry farms operate in the Republic of Kazakhstan, consisting of laying hens (for eggs), broilers (for meat), and hatcheries (for reproduction). In these areas, local residents are concerned about unpleasant odors caused by the decomposition of biological waste from poultry manure. Given the growing bird population on poultry farms, it is necessary to strengthen waste management measures (poultry manure) to reduce the negative environmental impact.

One potential solution to this problem is the implementation of biogas production projects using waste. The potential for biogas production from poultry waste in the Republic of Kazakhstan is presented in Table 2.

Table 2. Potential for Biogas Production from Poultry Manure

Biogas Source	Average Livestock, Million Heads	Biomass, kg/day per unit	Total Biomass, tons/day	Biogas Yield from 1 kg of Biomass, m³	Total Biogas Production, Thousand m³/day
Poultry Farms	33.8	0.17	5746	0.07	402.22
Farm Households	0.6	0.17	102	0.07	7.14
Household Farms	11.8	0.17	2006	0.07	140.42
Total	46.2	0.17	7854	0.07	549.78
Annual Biomass and Biogas Volume			2866710	-	200669.7

The analysis of the potential for biogas production from poultry manure shows that the largest volumes of organic waste come from poultry farms (5746 tons per day), while the smallest come from agricultural enterprises (102 tons per day). Poultry farms are the main source of biomass and biogas, as they have the largest bird populations. They can produce about 402.22 thousand m^3 of biogas per day. Households also contribute significantly (140.42 thousand m^3/day), despite having fewer birds than large poultry farms. This highlights the potential for using biomass from all sources, not just from industrial poultry farming.

The total daily biogas production in Kazakhstan can amount to approximately 549.78 thousand m^3, which equals about 200 million m^3 per year. This volume of biogas can be used for electricity generation, heating, or as fuel, reducing dependence on traditional energy sources and minimizing greenhouse gas emissions.

To realize this potential, the development of infrastructure for collecting, transporting, and processing poultry manure is necessary, as well as the installation of biogas plants at poultry farms and agricultural enterprises. Despite the fact that households collect 2006 tons of poultry manure daily, transporting it for biogas production requires significant financial investment. Therefore, biogas equipment should be installed at poultry farms and agricultural enterprises.

Thus, the potential for biogas production from poultry manure in Kazakhstan is quite large and could become an important source of energy, as well as an environmentally friendly method of disposing of poultry waste.

4.2 Mechanisms for State Support of Biogas Development

In order to select the most effective biogas projects and determine market competitive prices for electricity produced by biogas plants, the Rules for Organizing and Conducting Auction Trades were developed (2017). These rules include qualification requirements for auction participants, procedures for conducting the auction and submitting bids, types of financial guarantees, conditions for their submission and return, the procedure for summarizing results, determining winners, and more (Sitenko, 2023).

The main advantages of implementing the auction mechanism for state support of biogas development include:

Long-term guarantee for the purchase of electricity at a fixed price;

The possibility of participation by foreign companies;

Guaranteed access to land plots for the construction of bioenergy facilities.

To support the development of bioenergy in Kazakhstan, annual auctions are held to attract investors with state guarantees (Table 3).

Table 3. Results of Bioenergy Auctions in Kazakhstan, 2018–2022

Indicator	Unit of Measurement	2018	2019	2020	2021	2022
Auction Volume	MW	15	10	10	10	10
Selected during Auctions	MW	5	10.4	0	5.15	0
Starting Price	Tenge/kWh	32.23	32.15	32.15	32.15	32.15
Minimum Price	Tenge/kWh	32.15	32.13	-	31.14	-

In 2018, the auction volume was 15 MW, but starting from 2019, the volume was reduced and stabilized at 10 MW annually. In 2018, 5 MW of capacity was selected during the auctions, while in 2019, 10.4 MW was selected, exceeding the declared auction volume. In 2021, 5.15 MW was selected, which again was less than the declared auction volume. The decrease in the selected capacity during the auctions (0 MW in 2020 and 2022) is related to the fact that investors are not particularly eager to participate in biogas plant projects.

The starting price remained relatively stable throughout the analyzed period, with minor fluctuations. The presence of minimum prices lower than the starting price indicates competition among auction participants, although in recent years (2020 and 2022), data is absent, which could signal difficulties in the bioenergy market.

In recent years, Kazakhstan has observed a sharp decrease in the volume of electricity produced by biogas plants (Table 4).

Table 4. Production of Electricity from Biogas Plants in Kazakhstan, 2018–2022

Indicator	Unit of Measurement	2018	2019	2020	2021	2022
Installed Capacity	MW	0.3	2	8	8	2
Electricity Volume	million kWh	1	3	5	3	0.4
Purchase Costs	million Tenge	42	96	165	119	15
Average Purchase Tariff	Tenge/kWh	32.23	32.23	33.93	47.48	37.5

In 2018, the minimum installed capacity for bioenergy production was 0.3 MW. In the following years, a sharp increase in capacity was observed, reaching 2 MW in 2019 and a significant rise to 8 MW in 2020. The rapid growth in bioelectricity capacity to 8 MW in 2020–2021 indicates an expansion of the bioenergy sector during this period. However, the reduction in capacity to 2 MW in 2022 suggests possible difficulties or a decrease in interest in these projects.

During the analyzed period, electricity production increased from 1 million kWh in 2018 to a peak of 5 million kWh in 2020, after which it decreased to 0.4 million kWh in 2022.

State spending on purchasing electricity rose from 42 million tenge in 2018 to a peak of 165 million tenge in 2020. After 2020, spending began to decline, reaching just 15 million tenge in 2022. The increase in spending on electricity purchases in 2020–2021 was related to the growth in production volumes and rising tariffs. The sharp increase in the tariff in 2021 (to 47.48 tenge/kWh) may indicate an increase in the cost of bioelectricity production or a stimulus to encourage this sector.

The decrease in installed capacity and production volumes points to the need for investments in infrastructure and modernization of biogas plant equipment.

Biogas infrastructure in rural areas of Kazakhstan has significant socio-economic potential, contributing to the creation of new jobs, ensuring sustainable income and the formation of environmental responsibility among the population. The development of biogas plants requires the involvement of both technical specialists and local residents engaged in operational maintenance, logistics and agrotechnical processes. This creates the prerequisites for diversifying employment in agriculture and stabilizing income in the context of seasonality and instability of the agricultural market. In addition, the operation of biogas facilities helps to increase the level of environmental literacy of the rural population. People are beginning to realize the importance of proper waste management, the role of renewable energy sources in reducing greenhouse gas emissions and the benefits of replacing traditional energy sources. Through participation in training programs, farmers and young people acquire practical skills in the field of sustainable energy solutions, which directly fits into the goals of education for sustainable development and the formation of civic responsibility in the field of environmental policy. Thus, biogas projects not only contribute to the sustainable development of rural areas, but also perform an educational function, laying the foundations for the formation of an environmentally oriented society.

Financial support mechanisms (subsidies) are provided for the processing of poultry manure through composting and biogas installations. According to the Subsidy Rules for reimbursing part of the costs incurred by agricultural enterprises for investment in 2018, a subsidy of 11.6 million tenge is allocated for biogas installations.

In Kazakhstan, there are about a dozen farms or entrepreneurs who produce biogas from organic waste. Some of them even make a profit. For example, LLP "Agrofirma Kurma," located in the Karaganda region, is involved in poultry farming and has been using poultry waste for biogas production since 2018. This poultry farm also converts biogas into electricity, producing an average of 4.8 million kWh of electricity per year. The generated electricity not only covers the farm's internal needs but also generates profit by sending excess power to the national electricity grid (Alyokhova, 2023).

Despite the availability of state support and the experience of Kazakh farmers in biogas production, scaling up this positive experience is impossible without investment. The current state support mechanisms for biogas development are unattractive to investors and poultry farms. Therefore, for the sustainable development of biogas in Kazakhstan, the government should strengthen incentives for participation in auctions, possibly by increasing tariffs or providing additional subsidies.

4.3 Assessment of the Effectiveness of Biogas Production from Poultry Manure Based on a Two-Factor Correlation-Regression Model

Biogas production from poultry manure is a promising approach to solving environmental and energy-related problems associated with poultry farms. With the growing volumes of poultry farming and the accumulation of waste, converting poultry manure into biogas becomes an essential task for improving energy efficiency and reducing the environmental impact.

To achieve this, a two-factor correlation-regression model can be developed to describe the relationship between total biomass and the volume of biogas production.

Table 5. Data for calculating the parameters a_0 and a_1 in the model for poultry farms

Year	Million heads	Total biomass (ton/day)	Biogas production (m³/day)	x^2	$x \cdot y$
2018	32.4	5508	386	30,338,064	2,126,088
2019	32.8	5576	390	31,091,776	2,174,640
2020	30.8	5236	367	27,415,696	1,921,612
2021	35.6	6052	424	36,626,704	2,566,048
2022	37.3	6341	444	40,208,281	2,815,404
Total	168.9	28,713	2,011	824,436,369	57,741,843

After substituting the values from Table 3, the system of linear equations (2) will look as follows:

$$\begin{cases} 5a_0 + 28713a_1 = 2011 \\ 28713a_0 + 824436369a_1 = 57741843 \end{cases}$$

Solving this system, we get:

$$\begin{cases} a_1 = 0.0699 \\ a_0 = 0.97 \end{cases}$$

Thus, the desired model (1), reflecting the dependence of total biogas production on the total biomass derived from poultry, will be as follows:

$$\hat{y}_x = 0.0699 \cdot x + 0.97$$

Let us determine the reserves embedded in the independent (exogenous) factor. To do this, we will calculate the elasticity coefficient using formula (3).

$$E = 0.0699 \cdot \frac{5742.6}{402.2} = 0.988$$

Overall, we have the following:

1. The sign of the coefficient a_1 in the model aligns with the actual flow of processes in the economy and logic.
2. When the total biomass obtained from the poultry increases by 1%, the total biogas production will increase by 0.988%.

The evaluation of the model's quality showed the following results:

coefficient of determination (R^2) is equal 0.9999 – the model perfectly describes the relationship between total biomass and biogas production.

mean squared error (MSE) = 0.084 – the average squared deviation of the predicted values is small, indicating high model accuracy.

mean absolute error (MAE): 0.228 – On average, the model deviates by 0.228 thousand cubic meters per day when forecasting biogas production.

These metrics suggest that the model well represents the data and has high prediction accuracy.

Based on the linear regression model, forecasts of biogas production from poultry manure were calculated for five years (2025-2029). Additionally, for each year, a confidence interval was calculated at a 95% significance level, taking into account potential data fluctuations and the uncertainty of the model.

Table 6. Forecast of Biogas Production from Poultry Manure for 2025-2029

Year	Projected Biogas Production (thousand m³/day)	Lower Bound (thousand m³/day)	Upper Bound (thousand m³/day)
2025	506.96	505.11	508.82
2026	521.93	519.88	523.97
2027	536.89	534.65	539.14
2028	551.86	549.42	554.30
2029	566.83	564.18	569.47

The forecasted biogas production demonstrates steady growth over the five-year period. In 2025, the projected production is approximately 506.96 thousand m³/day, and by 2029, this figure is expected to increase to 566.83 thousand m³/day. The growth is driven by the expected increase in biomass, which is linked to the general trend of growing poultry farming and the accumulation of waste suitable for biogas production.

The confidence intervals for each year indicate a range of possible values, allowing for consideration of both the central forecast value and potential deviations. In 2025, the lower bound is 505.11 thousand m³/day, and the upper bound is 508.82 thousand m³/day. In 2029, the forecast range expands to 564.18 - 569.47 thousand m³/day, which reflects increased uncertainty as the forecast period lengthens. These confidence intervals demonstrate a high degree of confidence in the model's predictions, with relatively small deviations.

The average annual increase in biogas production is approximately 14-15 thousand m³/day. This figure can be used for further planning of biogas plant capacities and for assessing potential future energy resources.

The primary driver of the increase in biogas production is the rise in total biomass. The forecast based on biomass extrapolation for 2025-2029 shows a consistent upward trend. In 2029, biomass is expected to reach 8098.8 tons/day, compared to 7242 tons/day in 2025. This growth is an important factor in predicting biogas production growth.

Increased biogas production has positive implications for both the energy security of poultry farms and environmental sustainability. Growth in biogas production means a reduction in greenhouse gas emissions and efficient waste utilization. The additional volumes of biogas can be used for energy or fuel production, which in the long term may reduce dependence on fossil fuels.

Thus, the following conclusions can be made:

The forecasts for 2025-2029 indicate stable growth in biogas production, linked to the increase in available biomass.

The confidence intervals demonstrate a high level of accuracy in the model, although the degree of uncertainty grows as the forecast horizon extends.

The obtained results can be useful for planning the capacities of biogas plants and assessing the economic benefits of processing poultry manure into biogas.

5. Discussion and Conclusions

The implementation of biogas technologies based on poultry manure has both advantages and challenges, which must be considered for a comprehensive assessment of their efficiency and impact on agriculture and the environment.

Biogas technologies in agriculture, especially those utilizing poultry manure, hold great potential for addressing numerous pressing environmental, economic, and social issues. These technologies provide opportunities for more efficient use of organic waste, improvement of environmental conditions in rural areas, and reduction of energy costs. Consequently, biogas plants are becoming an essential element of sustainable agricultural development, enhancing the quality of life in local communities. The key benefits of these technologies can be grouped into three aspects: environmental, economic, and social advantages.

Environmental benefits:

1. Reduction of greenhouse gas emissions: utilizing poultry manure for biogas production reduces methane and ammonia emissions associated with traditional waste disposal methods, leading to improved environmental conditions in agricultural regions.
2. Waste management: biogas technologies enable efficient processing of organic waste, decreasing the need for traditional waste disposal methods such as landfilling or incineration, thus reducing environmental burdens.
3. Valuable by-product production: the residual material from biogas production (digestate) can be used as biofertilizer, offering an effective alternative to chemical fertilizers,

enhancing soil fertility, and reducing the costs of traditional fertilizers

Economic benefits:

1. Reduced energy costs: biogas can be used to generate electricity and heat, significantly lowering energy expenses for agricultural enterprises.
2. Income from biogas and electricity sales: excess energy generated can be sold to the national grid, providing an additional revenue stream for enterprises.
3. Savings on waste disposal: enterprises can cut costs associated with traditional waste disposal methods (transportation and landfilling) by adopting biogas systems.

Social benefits:

1. Job creation: the installation and operation of biogas plants require trained personnel, potentially creating new job opportunities in rural areas.
2. Improved living conditions in rural areas: reducing emissions and odors from poultry manure improves sanitation on farms and in surrounding areas, positively affecting the lives of local residents.

Despite significant environmental and economic benefits, the implementation of biogas technologies faces several major challenges that may hinder their widespread adoption, particularly in agricultural regions. High capital investment requirements, the need for regular process monitoring, dependency on biomass availability, and various regulatory barriers limit the scalability of these technologies (Figure 1).

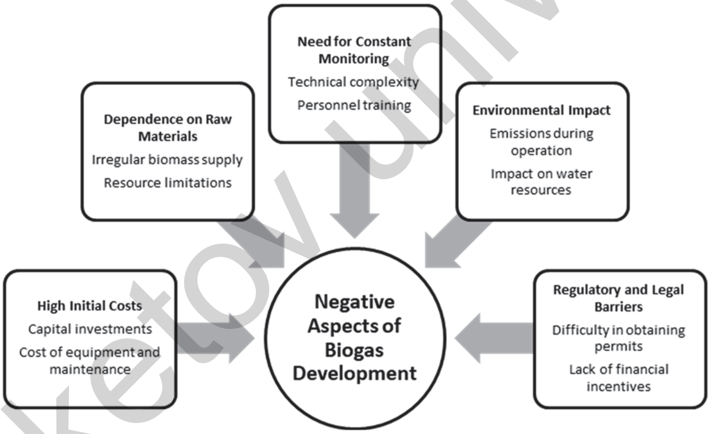

Figure 1. Negative aspects and factors hindering the development of biogas production from poultry manure

Consider the main negative aspects and factors that may hinder the effective implementation of biogas plants based on poultry manure:

Capital investments. The installation of biogas systems requires significant initial investments, which may be inaccessible for many farm businesses and poultry farms. Even with state support, the payback period can be quite long;

Cost of equipment and maintenance. Biogas plants require specialized equipment and regular technical maintenance, which increases operational costs;

Technical complexity. Managing the anaerobic digestion process requires constant monitoring and regulation of parameters such as temperature, humidity, and raw material composition. Any shortcomings in control can lead to reduced biogas production efficiency;

Staff training. For the effective operation of biogas plants, trained personnel are required, which increases the costs for the preparation and training of specialists;

Irregular biomass supply. Biogas production directly depends on the availability of organic feedstock (poultry manure), the volumes of which can fluctuate depending on the season or changes in production scale;

Resource limitations. If biomass production is insufficient to ensure the continuous operation of the plant, it may lead to reduced productivity and economic efficiency;

Emissions during operation. Although biogas technologies reduce greenhouse gas emissions, during operation, plants may emit hydrogen sulfide and other harmful substances if the cleaning system is ineffective;

Impact on water resources. Potential leaks and improper waste disposal can pollute groundwater and disrupt ecosystems near biogas plants;

Difficulties in obtaining permits. The process of obtaining permits for the installation and operation of biogas plants can be bureaucratically complicated and time-consuming, which slows down the implementation of these technologies;

Lack of financial incentives. Despite subsidies, many farmers and businesses may lack sufficient state support or access to loans to implement such projects.

Thus, biogas technologies based on poultry manure offer significant benefits, including economic advantages, environmental benefits, and social aspects. However, their implementation faces a number of challenges, such as high initial costs, dependence on raw material supply, and the need for constant technical control. To successfully scale these technologies, it is essential to develop state support, improve access to financing, and implement more efficient technological solutions.

In recent years, biogas technologies have been actively developing as part of sustainable energy and bioeconomy, while international experience demonstrates a variety of approaches depending on the institutional environment, level of decentralization, agricultural structure and degree of involvement of local communities. Particular attention is paid to the countries of Europe and Asia, where both successful models and systemic barriers to the implementation of biogas infrastructure are observed.

Thus, the experience of EU shows the high efficiency of integrating biogas plants into agriculture. According to the study by Sørensen and Jørgensen (2022), an increase in the processing of organic waste by 10% provides the creation of up to 342 jobs and an additional €21 million in income per year in Denmark. With full use of available biomass, the potential can reach more than 3 thousand jobs. An important aspect is institutional support and synergy between the agro-industrial sector and state sustainable development policy. In a study of bioenergy universes in Germany, Wüste and Schmuck (2012) emphasize that the trust factor between participants and participation in cooperative management ensure the long-term effectiveness of energy transformations. Social acceptance, inclusiveness and open communication are key elements for success. The Finnish experience presented in the study by Aro et al. (2025) highlights the differences between national and regional policies. In the North Savonia region, limited coordination mechanisms and a lack of project profitability are observed, which hinders the scaling up of the biogas system. The authors emphasize the importance of participatory planning with local actors and taking into account regional specific conditions. In addition, Hamman and Dziebowski (2025) analyze the organizational models of biogas supply chains in the EU, where success depends on the ability to create sustainable interactions between government agencies, agribusiness and technical providers. Social barriers, such as lack of trust, become an obstacle to horizontal cooperation.

In countries in South and Southeast Asia, energy poverty and the need for sustainable rural development are key drivers for biogas adoption. In India, as shown by Surie (2017), biogas ecosystems contribute to increasing food security and reducing dependence on fossil fuels. These systems rely on cross-sector cooperation, integration with agriculture and the active role of women in the management of the systems. Similar results are presented in the study by Katuwal (2022) for Nepal, where the national survey sample revealed that factors such as farm size, cattle ownership and income level are positively correlated with the likelihood of installing biogas systems. However, barriers remain significant, such as lack of access to finance and a shortage of qualified technical assistance. In Indonesia, Situmeang et al. (2022) identify four groups of barriers: technological (lack of suitable models), economic (high initial investment), social (low awareness) and environmental (waste concerns). These barriers require a comprehensive institutional response and the expansion of technical training programs.

Thus, international experience demonstrates that the key conditions for the sustainable implementation of biogas technologies are: 1) the presence of a coordinated government policy; 2) the active participation of local communities; 3) investments in human capital and technical support; 4) organizational flexibility and cross-sectoral interaction. These findings can be integrated into strategic planning for the development of biogas energy in countries with an agricultural focus, including Kazakhstan.

5.1 Renewable energy education and awareness raising

Raising environmental awareness and developing human resources are necessary conditions for the sustainable implementation of biogas technologies in agricultural regions. Empirical studies confirm that the integration of renewable energy sources (RES) and investments in human capital has a significant impact on reducing environmental degradation and greenhouse gas emissions. In particular, Kuziboev et al (2023) show that an increase in the educational level of the population and an increase in the share of RES in the energy balance of countries in Europe and Central Asia statistically significantly reduce the level of CO_2 emissions. The importance of trust and knowledge in the implementation of biogas technologies is confirmed by the results of studies in China. Thus, Zeng et al. (2022) found that training farmers through observation and recommendation mechanisms increases their willingness to use biogas, especially in conditions of high interpersonal trust in trainers. Similar findings are contained in the works of Ali et al. (2022) and Wang et al. (2023), which emphasize the importance of awareness-raising programs, farmer participation in training sessions, and coordination with government policies for the successful implementation of renewable energy sources in the agricultural sector.

These results emphasize the importance of an integrated approach, including the development of an educational environment and institutional support for the successful implementation of environmental initiatives, including biogas. In Kazakhstan, this approach was confirmed in the framework of the UNDP project "Introduction of Climate-Adapted Agricultural Technologies" (2023), which organized training for more than 400 farmers from 17 regions of the country. Familiarization with best practices in the use of biogas plants in agricultural production (including abroad) has increased the level of competence and awareness of target groups, which contributes to the dissemination and scaling of sustainable solutions in rural areas (UNDP, 2023).

Despite positive trends, one of the key barriers remains the lack of qualified specialists. The International Energy Agency (IEA, 2024) emphasizes that the lack of trained personnel in the field of renewable energy sources limits the development of the sector, especially in terms of technical maintenance and research support. In this context, it is advisable to strengthen cooperation with universities and research centers, as well as develop educational programs in the areas of "green" energy, including biogas. Thus, the development of the biogas sector should be accompanied by institutional and educational transformation aimed at creating sustainable knowledge, improving professional competencies and stimulating public trust in environmental innovations.

6. Conclusion

Based on the conducted analysis of biogas technologies based on poultry manure processing, the following conclusions can be made:

1. Biogas production from poultry manure represents significant potential for agricultural enterprises in Kazakhstan. It not only contributes to the efficient disposal of organic waste but also helps address energy security issues, reducing dependence on traditional energy

sources. Using biogas for heat and electricity generation can lead to lower energy costs for farms and poultry farms.

2. The implementation of biogas plants significantly reduces greenhouse gas emissions (such as methane and ammonia), which would otherwise occur during the traditional disposal of poultry manure. This not only improves the environmental situation in regions with developed poultry farming but also contributes to meeting environmental standards and mitigating climate impact.
3. Economic analysis shows that biogas plants can be profitable in the long term, especially with government subsidies and tax incentives. In addition to reducing energy costs, by-products from biogas production, such as biofertilizers, can provide additional income and help reduce expenses on chemical fertilizers.
4. To achieve maximum efficiency of biogas plants, a number of technical barriers must be overcome. These include the need for constant monitoring of process parameters, such as temperature and raw material composition, as well as technical support and staff training. High initial costs for installation and maintenance can be a barrier for many farming businesses, especially small and medium-sized ones.
5. For successful scaling of biogas technologies in Kazakhstan, it is crucial to expand government support programs, including subsidies for equipment installation and mechanisms to stimulate private investment. It is also necessary to simplify the permitting process for biogas projects and improve farmers' access to financial instruments.
6. Projections indicate that within the next five years, there could be a significant increase in biogas production volumes with the expansion of poultry farming and government support. This opens up opportunities for growth in the renewable energy sector in Kazakhstan, which can significantly improve the energy and environmental situation in agriculture.

Biogas technologies represent a promising direction for the agricultural sector in Kazakhstan. They not only solve the waste disposal problem but also offer opportunities for energy production and biofertilizer manufacturing. However, the successful implementation of such technologies requires significant investments, government involvement, and modernization of equipment. Key success factors include active government participation in the form of subsidies and tax incentives, technical staff training, and the introduction of modern technologies to enhance biogas plant efficiency. The prospects for the development of the biogas industry in Kazakhstan depend on coordinated efforts between the government, business, and the scientific community, which will enable the efficient use of this renewable resource, reduce environmental impact, and ensure sustainable development of agricultural enterprises.

The limitations of biogas production development in Kazakhstan include low investment attractiveness of projects due to high capital intensity and long payback periods, as well as insufficient interest of the private sector due to limited government support. In addition, there are still gaps in the regulatory framework regarding the regulation of organic waste processing, standardization of biofertilizers and the introduction of mandatory environmental requirements for agricultural enterprises. Infrastructure barriers related to the lack of logistics solutions for the collection and transportation of biomass in rural areas also remain significant.

The limitations of this study include the lack of systematized and detailed statistical information on key parameters necessary for in-depth analysis. At the current stage, the Republic of Kazakhstan does not fully account for the volumes of organic waste produced, in particular bird droppings, by regional, seasonal and technological characteristics. The lack of specialized industry registers and databases reflecting the characteristics of biomass and the operating parameters of existing biogas plants significantly reduces the possibility of accurate modeling and forecasting. Promising areas for future research may include the development of regionally differentiated models for supporting biogas projects, life cycle analysis of biogas plants, and assessment of the economic and environmental efficiency of co-fermentation of poultry manure with other types of waste. In addition, an important area is the institutional analysis of local government involvement and the development of educational programs for training specialists in the field of bioenergy, which will help create a sustainable professional environment in the agro-energy sector.

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