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Research Article

<https://www.jprra-kazniapk.kz><https://doi.org/10.46666/2026-3.2708-9991.07>**ECOLOGICAL AND ECONOMIC POTENTIAL OF BIOGAS PRODUCTION FROM DAIRY CATTLE BIOLOGICAL RESIDUES IN KAZAKHSTAN****ҚАЗАҚСТАНДАҒЫ СҮТ МАЛ ШАРУАШЫЛЫҒЫНЫҢ БИОЛОГИЯЛЫҚ ҚАЛДЫҚТАРЫНАН БИОГАЗ АЛУДЫҢ ЭКОЛОГИЯЛЫҚ-ЭКОНОМИКАЛЫҚ ӘЛЕУЕТІ****ЭКОЛОГО-ЭКОНОМИЧЕСКИЙ ПОТЕНЦИАЛ ПОЛУЧЕНИЯ БИОГАЗА ИЗ БИОЛОГИЧЕСКИХ ОСТАТКОВ МОЛОЧНОГО ЖИВОТНОВОДСТВА В КАЗАХСТАНЕ****A. BELGIBAYEVA****C.E.Sc., Associate Professor***S. ZHAPAROVA***C.Eng.Sc., Associate Professor***K. TURLYBEKOVA***Ph.D student**Sh. Ualikhanov Kokshetau University, Kokshetau, Kazakhstan*** corresponding author's e-mail: anar.belgibayeva@gmail.com***A.C. БЕЛЬГИБАЕВА****э.ф.к., қауымдастырылған профессор***С.Б. ЖАПАРОВА***т.ф.к., қауымдастырылған профессор***К.Е. ТУРЛЫБЕКОВА***Ph.D докторанты**Ш. Уәлиханов атындағы Көкшетау университеті, Көкшетау, Қазақстан***автордың электрондық поштасы: anar.belgibayeva@gmail.com***A.C. БЕЛЬГИБАЕВА****к.э.н., ассоциированный профессор***С.Б. ЖАПАРОВА***к.техн.н., ассоциированный профессор***К.Е. ТУРЛЫБЕКОВА***докторант Ph.D**Кокшетауский университет имени Ш.Уалиханова, Кокшетау, Казахстан*** электронная почта автора: anar.belgibayeva@gmail.com*

Abstract. Research Objective – to determine the ecological and economic prerequisites, prospects, and constraining factors of biogas production from dairy farming waste in Kazakhstan. **Methods** – content analysis of publications on this topic was used to systematize modern views on anaerobic digestion technologies and application directions for products derived from gaseous biofuels; the principle of comparison and synthesis – when comparing indicators of milk production, organic biological residue formation, and assessing opportunities for using them as a resource base for bioenergy gas production, summarizing the environmental and economic benefits of manure processing at dairy farms; summation of results – to substantiate vectors for the dissemination of biogas systems in the context of transition to a circular economy. **Results** – it was revealed that the potential volume of waste materials depends not only on cattle population, but also on the structure of the dairy herd, specifics of production process organization, and methods of manure removal and storage. It is noted that livestock numbers by categories of economic entities are of significant importance for characterizing animal housing and breeding. It is shown that households and peasant (farm) holdings predominate in the structure of the livestock sector, accounting for almost 90 % of total cattle numbers, which complicates the collection and transportation of manure substrate and reduces the efficiency of its centralized processing. It is established that due to territorial heterogeneity in dairy farming development, the potential for ecofuel generation in the republic should be considered differentially. Based on the obtained results, *conclusions* were drawn regarding the current state and prerequisites for constructing a circular model of agricultural production, enabling optimal resource consumption, generation of additional profit, and reduction of environmental burden.

Аңдатпа. Зерттеудің мақсаты – Қазақстанда сүт мал шаруашылығы қалдықтарынан биогаз өндірудің экологиялық-экономикалық алғышарттарын, келешегін және бөгеуші факторларын айқындау. Әдістері – осы мәселе бойынша жарияланымдардың контент-талдауы анаэробты ашу технологиялары мен газ тәріздес биоотын өнімдерін қолдану бағыттары туралы заманауи түсініктерді жүйелеу үшін пайдаланылды; салыстыру және синтез қағидаты – сүт өндіру, органикалық биологиялық қалдықтардың түзілу көрсеткіштерін салыстыру және оларды биоэнергетикалық газ шығару үшін ресурстық база ретінде пайдалану мүмкіндіктерін бағалау, сүт-тауарлы фермаларда қиды қайта өңдеудің экологиялық және экономикалық артықшылықтарын қорыту кезінде; қорытындыларды жинақтау – циркулярлық экономикаға өту жағдайында биогаз жүйелерін тарату векторларын негіздеу үшін. Нәтижелері – пайдаланылған материалдардың әлеуетті көлемі ІҚМ басынан ғана емес, сонымен бірге сүт табынының құрылымына, өндірістік процесті ұйымдастыру ерекшеліктеріне, қи массасын жою және сақтау тәсіліне байланысты екені анықталды. Шаруашылық жүргізуші субъектілердің санаттары бойынша мал басының саны жануарларды бағу мен өсіруді сипаттау үшін едәуір маңызға ие екені атап өтіледі. Мал шаруашылығы саласының құрылымында халық шаруашылықтары мен шаруа (фермер) қожалықтары басым екені көрсетілді, олардың үлесіне ірі қара малдың жалпы санының 90%-ға жуығы келеді, бұл қи субстратын жинауды және тасымалдауды қиындатады әрі оны орталықтандырылған қайта өңдеу тиімділігін төмендетеді. Сүт мал шаруашылығын дамытудың аумақтық әркелкілігінің болуына байланысты республикада биоотын генерациялау әлеуетін саралап қарастырған жөн екені белгіленді. Алынған нәтижелер негізінде ресурстарды оңтайлы тұтынуды, қосымша пайда алуды және экологиялық жүктемені азайтуды қамтамасыз етуге мүмкіндік беретін аграрлық өндірістің циркулярлық моделін құрудың қазіргі жай-күйі мен алғышарттары туралы қорытындылар жасалды.

Аннотация. Цель исследования – определить эколого-экономические предпосылки, перспективы и сдерживающие факторы производства биогаза из отходов молочного животноводства в Казахстане. Методы – контент-анализ публикаций по данной проблематике использован для систематизации современных представлений о технологиях анаэробного сбраживания и направлениях применения продуктов из газообразного биотоплива; принцип сравнения и синтеза – при сопоставлении показателей выработки молока, образования органических биологических остатков и оценки возможностей их задействования как ресурсной базы для выпуска биоэнергетического газа, обобщении экологических и экономических преимуществ переработки навоза на молочно-товарных фермах; суммирование итогов – для обоснования векторов распространения биогазовых систем в условиях перехода к циркулярной экономике. Результаты – выявлено, что потенциальный объем отработанных материалов зависит не только от поголовья КРС, но и структуры молочного стада, особенностей организации производственного процесса, способа удаления и хранения навозной массы. Отмечается, что численность скота по категориям субъектов хозяйствования имеет существенное значение для характеристики содержания и разведения животных. Показано, что в структуре животноводческой отрасли преобладают хозяйства населения и крестьянские (фермерские) хозяйства, на долю которых приходится почти 90% общего количества крупного рогатого скота, что усложняет сбор и транспортировку навозного субстрата и снижает эффективность его централизованной переработки. Установлено, что потенциал генерации экотоплива в республике в связи с существованием территориальной неоднородности развития молочного животноводства целесообразно рассматривать дифференцировано. На основе полученных результатов сделаны выводы о текущем состоянии и предпосылках построения циркулярной модели аграрного производства, позволяющей обеспечить оптимальное ресурсопотребление, получение дополнительной прибыли и сокращение экологической нагрузки.

Keywords: agriculture, dairy cattle farming, agricultural entities, dairy farms, livestock population, biogas, organic waste, anaerobic digestion.

Түйінді сөздер: ауыл шаруашылығы, сүт мал шаруашылығы, агроқұрылымдар, сүт-тауарлы фермалар, мал басы, биогаз, органикалық қалдықтар, анаэробты ашу.

Ключевые слова: сельское хозяйство, молочное животноводство, агроформирования, молочно-товарные фермы, поголовье скота, биогаз, органические отходы, анаэробное сбраживание.

Introduction

Dairy farming is an important source of food and one of the main branches of agriculture. Its development leads to the generation of significant amounts of organic waste, primarily manure. The lack of proper manure management can contribute to an increase in greenhouse gas emissions, air and water pollution. Maintaining the volume of milk production in the dairy sector should be carried out while reducing environmental impacts, which is one of the key tasks for the sustainable development of the industry [1].

The scale of this problem is particularly significant in countries with developed livestock production. Thus, some researchers draw attention to the formation of significant volumes of manure in the countries of the European Union and the United Kingdom, where up to 1.4 billion tons of livestock manure are produced annually from farms [2]. Only a small portion of this biowaste undergoes centralized collection and processing.

At the same time, it is advisable to consider manure not only as waste that needs to be disposed of, but also as a renewable resource with enormous energy and resource potential. Thus, the organic matter contained in it can be used as a raw material for the production of biogas by anaerobic digestion, and the digestate formed as a result of fermentation can be used as an organic fertilizer. This approach makes it possible to solve the problem of organic waste management, renewable energy production, as well as the return of nutrients to the agricultural cycle in parallel.

Currently, one of the most promising approaches of environmentally oriented agricultural development is the production of biogas from livestock waste, which will reduce the negative effects of traditional manure storage methods, reduce greenhouse gas emissions, replace fossil energy sources with renewable ones, and reuse anaerobic digestion products. From an economic point of view, the use of biogas plants will optimize the costs of enterprises related to the disposal and storage of manure, as well as reduce dependence on external energy sources. In addition, the processing of organic waste will provide additional sources of income generation as a result of the sale of biogas and digestate.

For Kazakhstan, this issue is of particular relevance in connection with the development of animal husbandry and, as a result, the formation of significant amounts of organic waste. Despite the availability of a sufficient number of studies on

the issues of animal waste management and biogas production, the environmental and economic aspects of the use of dairy farming waste in relation to the conditions of Kazakhstan are presented in fragments. Within the framework of this study, an attempt has been made to systematize and analytically summarize the environmental and economic aspects of biogas production from dairy farming waste, as well as to identify key opportunities, prospects and constraints to the development of this area in the country.

Literature review

Agricultural biomass, consisting of animal husbandry and crop production waste, is considered by many researchers as a promising renewable resource for energy production. The results of the study [3] indicate the significant potential of various types of agricultural waste as raw materials for biogas production. The study [4] emphasizes that animal manure contains a significant amount of organic matter that can be converted into biogas through anaerobic digestion.

In modern research, close attention is paid to improving the efficiency of anaerobic digestion and increasing the yield of biogas and methane. Alkaline pretreatment of manure has been shown to enhance anaerobic digestion efficiency, thereby increasing biogas and methane yields [5]. It has been shown that the effectiveness of pre-treatment depends on the type of manure, dry matter content, substrate composition, and the costs of pre-treatment [6].

Livestock manure is considered a promising raw material for anaerobic digestion in various types of bioreactors, which confirms the wide range of applications for animal husbandry waste [7]. The digestate formed after manure processing is important. Digestate can be used as a renewable organic fertilizer, influencing crop growth and the nutrient composition of the soil [8]. A comparative analysis reveals differences in the fertilizer potential of various forms of digestate obtained as a result of manure processing [9].

The economic aspects of biogas production are also complex. A number of studies show that the introduction of biogas plants can have a direct and indirect positive impact on agricultural productivity, time and resource savings, as well as the income structure [10]. At the same time, a number of studies highlight the high capital intensity of biogas projects, the significant initial investments required, and the need to ensure the stable operation of technological equipment [11].

Determining the potential of biogas production from livestock waste is a separate area of modern research. The volume of manure production and the potential for biogas generation depend on the structure of the livestock population and the spatial distribution of the animals [12]. The spatial approach makes it possible to determine the potential volume of manure processing at the regional level [13]. For Kazakhstan, the natural and climatic conditions and the structure of agricultural production are of particular importance. Studies indicate significant potential for biogas production from manure produced by livestock and poultry farms in Kazakhstan [14]. At the same time, they emphasize that the country's sharply continental climate limits the introduction of anaerobic digestion, since it requires additional costs to maintain optimal temperature conditions in biogas reactors.

The conducted research confirms the significant ecological and economic potential of animal waste processing. However, a comprehensive study of the environmental and economic aspects of biogas production from dairy farming waste, taking into account the specifics of Kazakhstan, remains insufficiently represented in the scientific literature.

Materials and methods

The research materials were based on scientific publications by domestic and foreign researchers devoted to the processing of livestock waste, anaerobic digestion, biogas production and sustainable development of the agricultural sector. A content analysis of research on this issue has allowed us to summarize data on anaerobic digestion technologies, the environmental effects of manure processing, and potential uses of the resulting biogas and digestate.

The empirical basis of the study based on official statistical data from the Bureau of National

Statistics of the Agency for Strategic Planning and Reforms of the Republic of Kazakhstan, as well as information and analytical materials from the Ministry of Agriculture of the Republic of Kazakhstan and other official sources. The work also uses regulatory and policy documents regulating the development of agriculture. The study analyzes current trends in the development of dairy farming in Kazakhstan and the formation of organic waste, primarily cattle manure. To assess the ecological and economic potential of biogas production, a comparative analysis method was used to determine the relationship between the scale of milk production, the formation of organic waste and the possibilities of their further use as a renewable resource potential.

The main environmental and economic advantages of manure processing on dairy farms are systematized using an analytical method. A comparative analysis of domestic and foreign experience has made it possible to identify the key conditions and limitations of dairy farming waste processing in Kazakhstan. The generalization method is applied to determine the prospects of using biogas technologies on dairy farms in the context of the transition to a circular economy and increasing the resource efficiency of agricultural production.

Results

To assess the current state of dairy farming in the Republic of Kazakhstan, the key quantitative and qualitative parameters of its development were studied. A comparison of cattle population sizes, cow's milk production volumes, and average milk yield per cow allowed us to identify the nature of structural changes and helped determine the role of cattle population and dairy herd productivity in determining milk production volumes. The results of this analysis are presented in table 1.

Table 1 — Dynamics of cattle population and cow milk production in Kazakhstan

Indicators	2023	2024	2025	Change, %	
				2025 /2023	2025 /2024
Cattle population, head	8 608 852	7 976 665	8 232 932	−4.4	+3.2
Cow milk production, tonnes	4 123 744.8	3 577 376.0	3 750 554.5	−9.1	+4.8
Average milk yield per dairy cow, kg	2 409	2 943	2 936	+21.9	−0.2
Note: compiled by the authors based on data from literature source [15]					

An analysis of the data presented in table 1 indicates an unstable trend in the scale of dairy production in the country. By the end of the analyzed period, the cattle population amounted to 8.23 million head, which is 4.4 % below the 2023 baseline. However, compared to 2024, there is a 3.2 % increase in the cattle population, indicating some recovery in the animal population. A similar trend can be seen in the dynamics of cow’s milk production. Thus, in 2025, cow milk production reached 3.75 million tonnes, which exceeds the 2024 production volume by 4.8 %.

However, this value is 9.1 % lower than the 2023 value. Thus, after a reduction in production indicators in 2024, the industry was able to demonstrate positive dynamics in 2025. However, its scale has not yet reached the 2023 level. A comparison of the obtained results suggests that increased dairy herd productivity has, to some extent, offset the decline in livestock numbers. However, average milk yield trends cannot serve as definitive evidence of increased dairy production efficiency, as they can be influenced by a variety of factors, including changes in herd structure, the increasing share of specialized dairy farms, and the specifics of statistical data collection and recording.

The identified dynamics should be taken into account when assessing the environmental impacts of dairy farming development. A reduction in the overall cattle population alone cannot be considered direct evidence of a proportional reduction in manure production. The potential volume of organic waste depends not only on the overall cattle population, but also on the number of dairy cows, the concentration of animals on specialized farms, the housing system, the temperature regime, the duration of housing, the manure removal and storage system, and other factors. Therefore, even with a relatively stable or declining cattle population, the concentration of

dairy production on large specialized farms can lead to the generation of significant localized volumes of organic waste, which will require effective management.

Therefore, the regional structure of the cattle population, the number of cows, and milk production is of particular importance for further analysis. Analyzing the regional structure helps identify areas with a high concentration of dairy production, which allows us to identify potential areas of organic waste accumulation and study the prerequisites for their processing using anaerobic digestion technology.

However, the high concentration of dairy cattle and milk production volumes in some regions cannot be equated with the actual biogas potential. Biogas potential depends on the availability of manure for collection, animal husbandry systems, and farm size. Nevertheless, this regional differentiation serves as a basis for assessing the potential for developing a resource base for biogas production and the subsequent environmental and economic benefits.

To obtain a more complete picture of the structure of dairy farming in the country, it is necessary to consider not only the dynamics of the total cattle population and milk production volumes, but also the distribution of livestock among different farm categories. The distribution of livestock by farm category is essential for assessing the organization of livestock farming, as the concentration of livestock in agricultural enterprises, peasant and farm enterprises, and private households determines production volumes and animal husbandry practices.

The structure of livestock distribution among farm categories determines the ability to organize the collection and subsequent processing of organic waste. The distribution of cattle by farm category in Kazakhstan is presented in table 2.

Table 2 — Distribution of the cattle population across farm categories in Kazakhstan

Farm categories	2023		2024		2025		Change (2025/2023)	
	cattle population, head	share, %	cattle population, head	share, %	cattle population, head	share, %	change in cattle population, head	share, percentage points
Agricultural enterprises	864 530	10	833 755	10.5	923 312	11.2	+58 782	+1.2
Peasant (farmer) farms and individual entrepreneurs	3 582 638	41.6	3 462 881	43.4	3 565 356	43.3	−17 282	+1.7



Household farms	4 161 684	48.4	3 680 029	46.1	3 744 264	45.5	–417 420	–2.9
Total	8 608 852	100	7 976 665	100	8 232 932	100	–375 920	–
Note: compiled by the authors based on data from literature source [15]								

The data presented in table 2 show that the majority of cattle in Kazakhstan remains concentrated in household and peasant farms.

In 2025, household farms accounted for 45.5 % of the total cattle population, peasant farms accounted for 43.3 %, while agricultural enterprises accounted for 11.2 %. This means that nearly 88.8 % of the cattle population was concentrated in household and peasant (farmer) farms within the domestic livestock sector.

At the same time, a comparison of 2025 data with 2023 data reveals a gradual shift in the livestock distribution structure. The share of agricultural enterprises increased by 1.2 percentage points (from 10.0 % to 11.2 %), the share of peasant (farmer) farms increased by 1.7 percentage points (from 41.6 % to 43.3 %). At the same time, the share of household farms decreased by 2.9 percentage points.

In absolute terms, a significant reduction in cattle numbers during the analyzed period was observed in household farms – by 417.4 thousand head, while in agricultural enterprises, the cattle population, conversely, increased by 58.8 thousand head. In peasant farms, the cattle population decreased slightly – by 17.3 thousand head. This trend may indicate a gradual redistribution of some cattle in favor of the large-scale commercial sector.

From the perspective of environmental and economic aspects of waste management, this structure is particularly significant. The concentration of cattle on household farms means a dispersed distribution of livestock. This can lead to additional logistical and organizational difficulties in the collection and transportation of manure and may also reduce the economic feasibility

of centralized manure processing in large-scale biogas plants. In turn, increasing the cattle population in agricultural enterprises and maintaining its importance in peasant (farm) households can contribute to the creation of more favorable conditions for organizing the regular collection of organic waste.

It should be noted that an enterprise's organizational and legal form alone cannot provide a sufficient or reliable basis for assessing the availability of manure for biogas production. The actual size of the farm, the concentration of livestock, the livestock housing system, and the manure disposal system play a decisive role.

Thus, analyzing the livestock population structure by farm category revealed one important structural feature of livestock farming in Kazakhstan: the combination of a significant proportion of dispersed livestock in households with the gradually increasing role of agricultural enterprises and peasant (farm) households.

For the development of biogas technologies, two different resource base development models can be applied: a dispersed model, associated with households, and a concentrated model, characteristic of organized agricultural enterprises and some peasant (farm) households. The second of these two models is aimed at creating more favorable conditions for the implementation of anaerobic digestion technologies, thereby ensuring a more stable supply of raw materials and reduced collection and logistics costs. Therefore, further analysis should focus on the regional concentration of dairy herds and milk production, as well as the potential for using the resulting manure in anaerobic digestion technologies (table 3).

Table 3 — Regional distribution of the cattle population and cow milk production, %, 2023-2025

Region	2023			2024			2025		
	share of national total, %			share of national total, %			share of national total, %		
	of total cattle population	dairy cow population	cow milk production	of total cattle population	dairy cow population	cow milk production	of total cattle population	dairy cow population	cow milk production
Abay	8.1	8.6	1.6	8.8	9.1	8.3	9.0	9.4	8.4
Akmola	5.3	4.9	8.1	4.8	4.2	6.6	4.8	4.2	6.4
Aktobe	7.8	7.7	6.3	7.6	8.3	4.9	7.3	8.0	4.8

Almaty	7.6	8.6	7.7	7.2	7.4	8.1	7.1	7.5	8.2
Atyrau	2.4	2.5	0.1	2.8	3.0	0.9	2.9	3.1	0.8
West Kazakhstan	10.0	8.9	0.5	11.6	11.3	5.8	12.4	11.8	5.7
Zhambyl	6.2	4.8	6.6	5.4	4.7	6.3	5.4	4.8	6.1
Zhetisu	6.0	5.8	5.0	6.1	5.7	6.0	6.0	5.7	6.0
Karagandy	5.7	5.6	7.1	5.4	5.7	5.9	5.2	5.5	5.8
Kostanay	5.5	5.2	8.8	5.0	4.6	5.8	4.8	4.6	6.0
Kyzylorda	4.8	5.1	1.4	4.6	5.1	1.5	4.5	5.0	1.5
Mangystau	0.2	0.3		0.2	0.3		0.3	0.3	–
Pavlodar	5.6	5.8	8.4	5.9	6.0	6.6	5.8	5.9	6.8
North Kazakhstan	4.4	4.7	13.9	3.5	3.2	10.4	3.4	3.2	10.2
Turkistan	12.6	13.4	15.1	13.5	13.5	12.5	13.7	13.4	12.6
Ulytau	1.7	2.3	2.0	1.9	2.3	1.8	1.8	2.1	1.7
East Kazakhstan	5.1	5.2	6.1	4.5	4.6	6.7	4.5	4.5	6.9
Republic of Kazakhstan	100	100	100	100	100	100	100	100	100

Note: compiled by the authors based on data from literature source [15]

The data presented in table 3 demonstrate significant territorial differentiation in dairy farming in Kazakhstan. The different levels of specialization and productivity of dairy production in individual regions of the country are a consequence of significant differences in the regional structure of cattle populations and cow's milk production.

In 2025, cattle populations were concentrated primarily in the Turkistan Region (13.7 %), West Kazakhstan Region (12.4 %), and Abay Region (9.0 %). In terms of milk production, the leaders in cow's milk production are the Turkistan Region (12.6 %), Abay Region (8.4 %), Almaty Region (8.2 %), and North Kazakhstan Region (10.2 %). Thus, a large cattle population does not always correspond to a proportional regional contribution to milk production.

Regional differentiation is most clearly evident when comparing their shares in the cow population and milk production. Thus, in 2025, the North Kazakhstan Region, with a share of only 3.2 % of the national dairy cow population, accounted for 10.2 % of cow milk production. A similar picture is observed in the Akmola Region, where 4.2 % of the cow population accounts for 6.4 % of milk production nationwide, and in the East Kazakhstan Region – 4.5 % and 6.9 %, respectively.

The opposite trend is observed in the West Kazakhstan Region, where the share of cows was 11.8 %, while their share in milk production was half that, at 5.7 %. A similar situation is observed in the Aktobe Region — 8.0 % and 4.8 %. These

disparities reflect differences in the productivity and structure of dairy farming and make it possible to identify regions with a higher concentration of specialized dairy production. Over the analyzed period, the distribution of livestock among farms of various legal forms underwent certain changes. The largest increase in the share of the national cattle population was observed in the West Kazakhstan Region (from 10.0 % to 12.4 %) and the Turkistan Region (from 12.6 % to 13.7 %).

In the North Kazakhstan region, the share of cattle in the cattle population decreased by 1.0 percentage point (from 4.4 % to 3.4 %), and the share of milk production decreased by 3.7 percentage points (from 13.9 % to 10.2 %). However, despite its relatively small share of livestock, North Kazakhstan Region maintains a significant contribution to milk production in the country. The Almaty, Akmola, and East Kazakhstan regions also remain among the leading regions, where the share of milk production exceeds the share of cows.

These identified differences are fundamental when considering the prospects for processing dairy farm waste. As noted above, the potential resource base for biogas production depends less on the total cattle population and more on the concentration of dairy herds, the size of dairy farms, and the capacity for organized manure collection. Consequently, regions with a relatively high milk production volumes and a lower cow population may be of great interest for the implementation of anaerobic digestion technologies. At the same

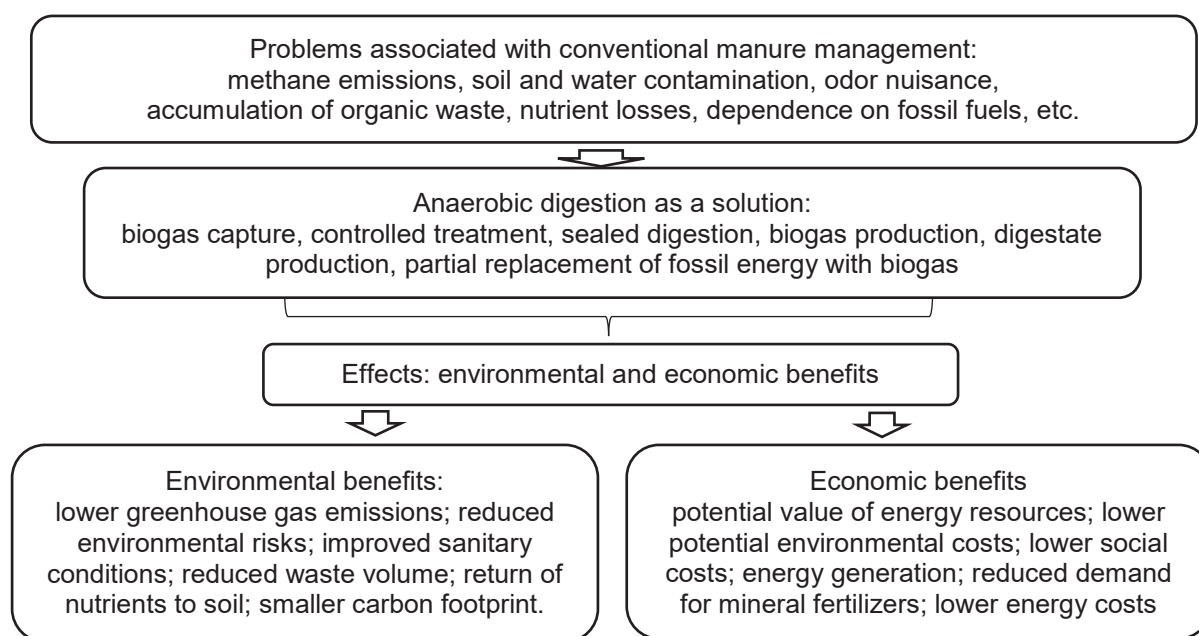
time, regions with large cattle populations may also be potentially attractive, but here, attention must be paid to the livestock production structure and the proportion of manure available for centralized collection and processing. Thus, regions across the country have different prerequisites for the implementation of biogas technologies.

The territorial concentration of dairy farming can be considered one of the factors determining the potential scale of organic waste generation and subsequent processing. It should be noted that data on cattle population alone are insufficient to determine the potential volume of feedstock for biogas production. The proportion of dairy cattle, the existing animal housing system, the duration of the confinement period, and the availability of organized manure collection are more significant.

Therefore, it can be noted that the higher the concentration of dairy cattle and the scale of milk

production, the greater the potential volume of manure generated, requiring organized collection, storage, and disposal. This creates a dual situation: on the one hand, manure is an inevitable byproduct of production, increasing the environmental impact, but on the other, it is a valuable organic raw material.

Thus, biogas production from dairy waste should be considered not only as a technological solution to the problem of manure utilization, but also as a key element in developing a circular agricultural production model. This model creates the preconditions for closing the resource cycle. The economic and environmental value of this model lies in the possibility of simultaneously reducing waste management costs, substituting for some traditional energy resources, generating additional organic fertilizer, and mitigating potential environmental damage (figure 1).



Note: compiled by the authors based on data from literature source [16]

Figure 1 — Environmental and economic impact of dairy manure recycling

Thus, dairy manure processing serves both as a tool for environmental modernization and as a way to improve the resource efficiency of dairy farming. In other words, biogas production transforms manure from a waste product into a secondary renewable raw material.

The accumulation of organic waste without effective management systems can lead to the release of methane and other pollutants, odors, increased risks of soil and water pollution, and increased losses of nutrients contained in manure. Thus, traditional manure storage and disposal not

only increase environmental costs but also economic costs associated with the construction and maintenance of storage facilities, waste transportation, and the development and implementation of preventative measures aimed at preventing negative environmental impacts.

At the same time, dairy manure is known to have significant resource potential, as the organic matter it contains can be converted into biogas through anaerobic digestion. This process converts dairy waste into a secondary energy resource.

A combination of various factors determines the environmental and economic feasibility of constructing biogas plants in specific regions. Factors determining the economic feasibility of biogas production include the following: the size of the dairy farm, the amount of manure, its availability for collection, the moisture content and composition of the feedstock, the dry matter and organic matter content, the livestock management system, the cost of biogas plant construction, manure transportation logistics, government support for renewable energy sources, the use of digestate as fertilizer, the possibility of selling or using the energy internally, etc.

Due to the regional differences in the development of dairy farming, it is advisable to consider the prospects for biogas production in Kazakhstan in a differentiated manner. In regions with a high concentration of dairy herds and well-established specialized production, the most promising option may be the implementation of large-scale biogas complexes. These include the North Kazakhstan, Akmola, Almaty, and East Kazakhstan regions, where the ratio of livestock to milk production indicates a relatively high concentration of dairy production. In areas with a lower concentration of livestock, local installations designed to process waste from individual farms or cooperative associations may be potentially effective.

Discussion

This study demonstrates that biogas production from dairy farming waste can be considered a promising area for the development of the bioeconomy and circular agriculture in Kazakhstan. The use of organic waste as a raw material for energy production contributes to increased sustainability of agricultural production and more rational use of bioresources. The obtained results are consistent with previously published studies in which this approach is considered an important tool for the effective use of resource potential and for strengthening the competitive advantages of the agricultural sector [16].

The use of circular economy principles in dairy farming allows for a comprehensive solution to the problem of environmental sustainability and economic efficiency in the industry. At the same time, it should be borne in mind that the transition to a circular economy is associated with significant financial requirements, the need to improve management mechanisms, and the provision of comprehensive, systemic state support [17].

The economic efficiency of biogas production has also received significant attention in the research of foreign scientists. In addition to the

energy effect, biogas production can provide additional socio-economic benefits, including job creation and increased incomes [18]. This suggests that the development of biogas production in Kazakhstan could have a broader impact, stimulating employment and promoting the socioeconomic development of rural areas.

Thus, biogas production from dairy farming waste can be considered a comprehensive approach combining environmental and socioeconomic benefits. In Kazakhstan, the development of this approach has significant potential due to the possibility of combining the processing of dairy farming waste with the simultaneous production of renewable energy and organic fertilizers.

Conclusions

1. The efficiency of biogas production is influenced by a combination of technological, environmental, and economic factors, the specifics of which in the Republic of Kazakhstan remain insufficiently studied, confirming the relevance of a comprehensive assessment of the environmental and economic potential of dairy waste recycling.

2. The potential for biogas production in Kazakhstan depends not only on the total cattle population but also on the level of dairy farming concentration, ensuring organized manure collection, as well as on the cattle housing system, temperature regime, and duration of housing, manure removal and storage systems, etc.

3. The distribution of livestock by farm category is essential for assessing the organization of livestock farming. The structure of livestock farming in Kazakhstan is characterized by a predominance of household and peasant farms, which account for almost 90 % of the total cattle population. This characteristic indicates a highly dispersed resource base, which should be taken into account when planning livestock waste collection and recycling systems.

4. The concentration of cattle on household farms can lead to additional logistical and organizational difficulties in the collection and transportation of manure, as well as reduce the economic feasibility of centralized manure processing in large biogas plants. The shift in the production structure toward agricultural enterprises and peasant (farmer) households creates the preconditions for more efficient organization of manure collection and processing, which expands the potential for the implementation of biogas technologies.

5. The prospects for biogas production in Kazakhstan are linked to regional characteristics of dairy farming development. The country's re-

gions have different prerequisites for the implementation of biogas technologies. In regions with a high concentration of dairy livestock, the creation of large-scale biogas complexes is most feasible, while in other areas, localized installations may be more effective.

6. The use of dairy waste for biogas production is a promising area for the development of a circular agricultural production model, allowing for more efficient use of resources, generating additional profits, and reducing environmental impacts.

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