The object of this study is the greenhouse gas (GHG) emissions generated in livestock farming, primarily methane (CH_4) from enteric fermentation and nitrous oxide (N_2O) from manure management processes. The problem under study is the lack of instrumental methods and national programs for measuring and reducing emissions from confined animals, which results in excessive methane release and inefficient manure utilization.

Based on inventory data, the results show that annual agricultural emissions amount to 20,982.25 thousand tons of CO_2-eq. methane (58% of agricultural GHGs) and 15,239.72 thousand tons of CO_2-eq. nitrous oxide (42%), with a total of 319.547 million tons of CO_2, 2.313 million tons of CH_4, and 0.058 million tons of N_2O released in 2018. Interpretation of these results confirms that improper manure storage, outdated technologies, and the absence of biogas recovery systems are the main contributors to elevated GHG emissions worldwide.

The distinctive feature of this research is the development of autonomous climate-friendly bioenergy systems equipped with solar collectors and bioreactors that convert animal waste into biogas and organic fertilizer. This innovative technological solution not only explains the mechanisms of emission reduction but also demonstrates how livestock enterprises can generate renewable thermal and electrical energy, covering up to 80–85% of their total energy demand. The practical significance of the study lies in demonstrating how the integration of such biogas technologies can improve environmental safety, reduce dependence on fossil fuels, enhance long-term energy resilience, and promote sustainable agricultural development on a global scale

Keywords: energy-saving technologies, microclimate systems, renewable energy sources, biogas plants, waste disposal

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DETERMINATION OF THE POSSIBILITY OF USING BIOGAS TECHNOLOGIES FOR THE INTRODUCTION OF ENERGY-SAVING SYSTEMS MICROCLIMATE

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1. Introduction

Agriculture, and in particular livestock production, remains a central driver of greenhouse gas (GHG) emissions worldwide. According to the IPCC, the agricultural sector contributes significantly to global methane (CH_4) and nitrous oxide (N_2O) emissions, gases, which warming potential is 28 and 265 times higher than CO_2, respectively. Their accumulation in the atmosphere not only accelerates climate change but also poses serious challenges to sustainable food production and rural development.

For countries with large pastoral and mixed farming systems, such as Republic of Kazakhstan, the problem is particularly acute. Animal husbandry accounts for almost half of gross agricultural production, and the growth of the sector increases the volume of manure and associated emissions. In 2018, Republic of Kazakhstan's total GHG emissions reached 408.88 million tons of CO_2-eq., of which agriculture contributed more than 36 million tons, placing it second after the energy sector. Despite this, environmentally sustainable waste treatment and emission reduction technologies remain insufficiently applied, and most farms lack modern manure management systems.

The relevance of this topic extends beyond Republic of Kazakhstan. Globally, the search for effective ways to mitigate agricultural GHG emissions has become a priority of climate policy and agricultural science. The technologies such as anaerobic digestion can simultaneously reduce emissions, improve nutrient cycling, and generate renewable energy. This dual environmental and economic benefit highlights the importance of continued research in this area.

Therefore, research on greenhouse gas emissions from livestock farming and the development of integrated waste-to-energy systems is highly relevant, as it addresses urgent issues of climate change mitigation, energy security, and sustainable agricultural development.

2. Literature review and problem statement

A review of existing studies reveals that research on greenhouse gas (GHG) emissions from livestock production has primarily focused on specific emission sources, management practices, or mitigation measures, yet key gaps remain in integrating these findings into coherent, farm-scale strategies. The study [1] emphasized that nitrogen management practices under different irrigation regimes strongly affect nitrous oxide emissions, but the challenge of maintaining crop yield while minimizing emissions remains unresolved. The variability of soils and climates complicates the development of universal fertilization recommendations, highlighting the need for adaptive, site-specific management models.

Similarly, paper [2] demonstrated the feasibility of precise methane and ammonia monitoring in barns but noted difficulties in addressing spatial variability and the high cost of long-term measurements. These technical and economic barriers limit the practical application of emission control at the farm level.

Research in paper [3] revealed significant regional disparities in agricultural GHG efficiency, underscoring the need for harmonized assessment methods and targeted mitigation policies. However, heterogeneity in farm structures and production intensity makes cross-country comparability difficult and hampers policy standardization.

According to paper [4], urease inhibitors effectively reduce ammonia emissions, yet their adoption is constrained by high costs and insufficient policy support. The lack of integrated manure management systems further limits the overall mitigation potential.

The work in paper [5] established a link between animal health, productivity, and GHG intensity but found that the complexity of biological interactions prevents a clear definition of mitigation pathways. Similarly, papers [6] and [7] highlighted that nutritional and genetic factors can influence methane emissions, though variability among breeds, feed types, and environmental conditions restricts the scalability of such interventions. Trade-offs between productivity and emission reduction remain a persistent challenge.

Finally, paper [8] summarized the main drivers of ruminant methane production feed quality, digestion efficiency, and housing conditions while pointing out the lack of practical frameworks for applying laboratory findings to real farm settings. The transition from experimental studies to full-scale, economically feasible mitigation systems remains largely unresolved.

Overall, the literature indicates that existing studies address isolated aspects of livestock GHG emissions but do not provide a unified, implementable solution adaptable to diverse farming environments. The main unresolved problem lies in the absence of integrated, context-specific approaches that combine emission monitoring, manure management, and renewable energy recovery technologies such as biogas systems.

3. The aim and objectives of the study

The aim of this study is to assessment of the possibility of using biogas technologies for the implementation of energy-saving microclimate systems in livestock farming in the Republic of Kazakhstan, contributing to the reduction of greenhouse gas emissions and the improvement of environmental sustainability. This will allow the development of practical solutions for sustainable agricultural production, energy efficiency, and improved manure management.

To achieve this aim, the following objectives are accomplished:

– to quantify methane and nitrous oxide emissions from livestock manure management and enteric fermentation, which will allow identification of the main sources and reduction priorities;

– to analyze the potential of biogas production from organic waste as a source of renewable energy and fertilizer, which will allow justification of its role in enhancing energy independence and circular agriculture.

4. Materials and methods

The object of this study is the greenhouse gas (GHG) emissions generated in livestock farming, primarily methane (CH_4) from enteric fermentation and nitrous oxide (N_2O) from manure management processes.

The main hypothesis of the study is that the implementation of integrated biogas and energy-saving microclimate systems can significantly reduce methane and nitrous oxide emissions while simultaneously producing renewable energy and organic fertilizer for agricultural use.

The assumptions made in the study include uniformity in livestock management practices across regions, stable feed composition and energy content throughout the year, and the predominance of confined cattle housing systems typical for Kazakhstan's climatic zones.

The simplifications adopted involve the application of average national emission coefficients adjusted for local conditions, exclusion of short-term climate variability, and reliance on default IPCC factors where regional data were limited.

The present study focuses on the assessment of methane (CH_4) and nitrous oxide (N_2O) emissions from livestock production systems in the Republic of Kazakhstan, with an emphasis on enteric fermentation and manure management processes in cattle breeding. These processes are considered the dominant sources of agricultural greenhouse gases and represent key areas for mitigation through the introduction of integrated manure utilization and biogas recovery technologies [9, 10]. The main sources of methane and nitrous oxide emissions in livestock systems are illustrated in Fig. 1.

The research utilized both national and international data sources. Statistical information on livestock numbers, types, and production parameters for 2014–2020 was obtained from the Bureau of National Statistics of the Republic of Kazakhstan [11]. Additional materials included the national greenhouse gas inventory reports submitted to the UNFCCC, the IPCC Guidelines for National Greenhouse Gas Inventories (2006, 2019 Refinement), and relevant scientific publications on emission coefficients and manure management systems [12–14]. Table 1 presents general information on greenhouse gas emissions in Republic of Kazakhstan's agricultural sector for 2014–2018, which served as a baseline for further calculations.

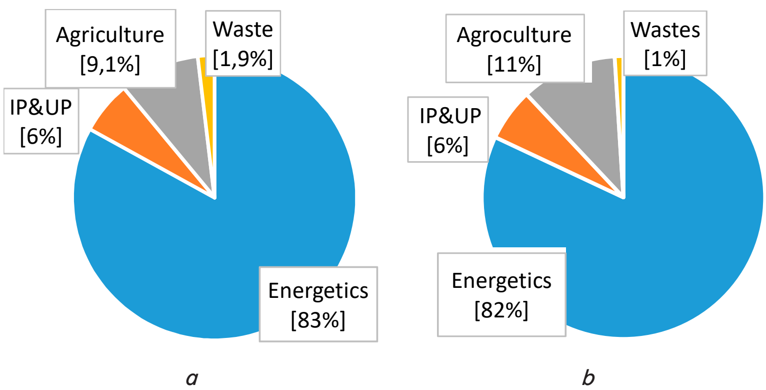

Fig. 1. Total national emissions by sector agriculture in Republic of Kazakhstan: *a* — in 1990; *b* — in 2018

Table 1

Emissions of major GHGs into the atmosphere for 2014—2018 years

S. No.	Name	Unit of measurement	2014	2015	2016	2017	2018
1	Carbon dioxide, CO_2	million tons per year	256.672	263.590	267.693	283.291	319.647
2	Methane, CH_4	million tons per year	2.082	2.019	2.055	2.107	2.313
3	Nitrous oxide, N_2O	million tons per year	0.053	0.054	0.053	0.054	0.058

The estimation of methane emissions from enteral fermentation of cattle and farm animal manure (E) contained in isolated livestock premises is estimated as the number of animals (N_i) and the coefficient of methane emissions from group i-animals in kilograms of CH_4 (K_i), according to the equation [15]

$$E = \sum_{i=1}^{\infty}\left(N_i \times / Ki\right). \qquad (1)$$

To assess CH_4 emissions from farm animals E, the study used the main detector of livestock development in all categories of farms, specifically number of cattle and methane emissions from enteral fermentation and manure for 2020 in Republic of Kazakhstan. To establish the coefficient of specific CH_4 emission (EF) for the categories of animals with the greatest contribution to the emission from enteral fermentation of ruminants or non-ruminants, it is customary to use the calculation formulas given [16]. These equations allow to calculate the gross energy consumption of animal feed, based on the ratio of feed types in the annual ratio of livestock and statistical data on the total feed consumption per 1 livestock of cows and other cattle [17]. The coefficient of a specific emission of CH_4 is calculated by the equation

$$EF = \left(GE \times Y_m\right) / 55.65 M_j / \text{kg } CH_4, \qquad (2)$$

where GE – the gross energy of feed consumed per livestock per year, M_j;

Y_m – the conversion coefficient of gross energy into CH_4 in the intestinal tract of cattle;

55.65 – a coefficient representing the energy content of CH_4.

Since Republic of Kazakhstan is closer to the conditions of Asian countries than Eastern Europe in terms of agro-climatic conditions of cattle grazing, the study chose CH_4 emission coefficients as in developing countries [18]. Then the coefficients of methane emission from enteral fermentation for the whole year, i.e., 365 days, for dairy cattle will be equal to 56 kg CH_4/livestock/year, and for non-dairy cattle 44 kg CH_4/livestock/year [19, 20]. After clarifying the number of livestock for the year and selecting the values of the coefficient of a specific emission of CH_4, methane emissions are determined by the following formula

$$\text{Emissions } CH_4 = EF \times N_{livestock} / \left(10^6 \text{ kg/Gg}\right), \qquad (3)$$

where Emissions CH_4 – methane emissions as a result of enteral fermentation, Gg CH_4/year;

EF – the coefficient of specific CH_4 emissions for a specific cattle population, kg of CH_4/livestock year;

$N_{livestock}$ – the number of animals.

To determine the conversion coefficient of gross energy into CH_4 in the intestinal tract of cattle (Y_m), which is the proportion of gross energy in feed reformed into methane, tabular given data were used in this study [21]. At the same time, it should be borne in mind that the parameters of this coefficient given in Table 3 are an approximate guideline by general characteristics of feed and industrial practice existing in many countries. Clarifications of the value of gross energy of the feed consumed per 1 livestock of cattle per year (GE) are made by the type of diet given in [22, 23]. The parameters of the gross energy coefficient of the feed consumed are given in Table 4.

A significant contribution to the total emission of CH_4 and N_2O is made from ruminant animal waste as a result of manure harvesting, storage, and processing. In conditions of keeping a significant number of animals in a confined space, manure is usually disposed of in liquid systems, which leads to the formation of CH_4. Wherein the main factor influencing methane emission is the amount of manure produced and the proportion of manure that undergoes anaerobic decomposition. According to, the calculation of methane emissions from manure storage systems is carried out according to the formula

$$\text{Emissions } CH_4 = \sum\left[EF \times N_{livestock} / \left(10^6 \text{ kg/Gg}\right)\right], \quad (4)$$

where Emissions CH_4 – methane emissions as a result of manure harvesting, storage, and use, Gg CH_4/year;

EF – the coefficient of annual CH_4 emissions for a given category of livestock, kg CH_4/livestock*year;

$N_{livestock}$ – the number of animals, livestock.

Table 3

Methane conversion coefficient for cattle [24]

Livestock type	Y_m
Cattle fattened on a feed yard when feed rations contain 90% concentrate or more	3.0% +/–1.0%
Dairy cows and heifers	6.5% +/–1.0%
Other cattle fed on crop residues and by-products	6.5% +/–1.0%
Other livestock – pasture	6.5% +/–1.0%

Table 4

Coefficients of gross energy consumption *GE*, MJ/livestock/day

Ration type	*GE*, MJ/(kg dry matter)
Ration high in grains > 91%	7.5–8.5
High quality fodder (e.g. vegetative mass of beans and herbs)	6.5–7.5
Medium class fodder (e.g. mid season beans and herbs)	5.5–6.5
Poor class fodder (e.g. straw, mature herbs)	3.5–5.5

Determination of the value of the coefficient of a specific emission of CH_4 as a result of harvesting, storage, and the use of manure is carried out using the equation

$$EF = \left(VST \times 365\right) \times \times \left\lfloor Do \times 0.67 \text{ kg/m}^3 \times \sum\left(MCF \times 100\right) \times MS \right\rfloor, \quad (5)$$

where *VST* – the daily release of volatile solid matter for this category of livestock, kg/livestock*year;

365 – the basis for calculating the annual production *VS*, day/year%;

Bo – the maximum potential of CH_4 emissions from manure (0.24 ± 0.04; 017 ± 0.03 for cows and other cattle) m^3 CH_4/kg of allocated VS;

MCF – the conversion factor of CH_4 for different types of manure storage systems (in liquid form: 20.0 (–2.0 / +5.0%), in solid form: 2.0 (–0.1 / +0.6%));

MS – a fraction of cattle manure contained in a certain collection and storage system;

0.67 – the conversion coefficient of m^3 CH_4 to kilograms CH_4, kg/m^3.

The coefficients of CH_4 emissions for various types of cattle from methane emissions from manure collection, storage, and disposal systems are equal: for dairy cattle – 4.6 kg of CH_4/livestock/year, for non-dairy cattle – 2.64 kg of CH_4/livestock/year.

To determine the N_2O emissions accumulated from the manure collection, storage, and disposal system, used the formula. Given in, by the revised version. Wherein the values, the nitrogen emission coefficient, EF3, for various manure storage systems are equal to:

– with a liquid storage system – 0.001;

– when stored in solid form and on pastures – 0.02.

The coefficients of nitrous oxide emission from animal manure according to [25] are set: for dairy cattle – 89.64 kg N_2O/livestock per year, and for non-dairy cattle – 53.5 kg N_2O/livestock per year. To estimate the emission of N_2O during the storage and use of manure, it is possible to use the formula

$$\text{Emission } N_2O\left(AWMS\right) = = \sum\left(N_{in}\left(AWMS\right) \times EF\left(AWMS\right)\right) \times 44/28, \quad (6)$$

where N_2O(*AWMS*) – the total direct emission of N_2O from manure collection and storage systems; kg N/year;

N_{in} (*AWMS*) – the intake of nitrogen contained in manure under this system of storage and use of animal waste, kg/year;

EF(*AWMS*) – the N_2O emission coefficient for AWMS (kg·N_2O – N/kg N_{in} (*AWMS*)).

The nitrogen contained in the manure released by a certain number of animals (*N*(*T*)) is determined by

$$Nex\left(AWMS\right) = = \sum\left(N\left(T\right) \times Nex\left(T\right) \times AWMS\left(T\right)\right), \quad (7)$$

where *Nex*(*T*) – the release of nitrogen contained in animal manure, kg per livestock per year;

ARMS(*N*) – the share of *Nex*(*T*) that accounts for this waste storage and use system. To ensure consistency, all coefficients and parameters were adjusted to Republic of Kazakhstan's climatic zones and prevailing livestock management practices. The resulting emissions were converted into carbon dioxide equivalents (CO_2-eq) using standard global warming potential values of 28 for CH_4 and 265 for N_2O.

Several simplifying assumptions were made: the average feed composition and digestibility coefficients were assumed constant across regions; climate-related corrections were not applied; emission factors correspond to IPCC default values adjusted for local conditions. The study focused primarily on cattle, which account for more than 80% of total livestock methane emissions in the country.

The methodology described above provided the basis for estimating methane and nitrous oxide emissions in the following section. The obtained values were further analyzed to determine biogas production potential and environmental benefits of waste-to-energy integration in livestock farming systems.

5. Research results of possibility using biogas technologies for energy-saving microclimate systems in livestock farming

5. 1. Quantification of methane and nitrous oxide emissions from livestock

Using the calculation formulas (3)–(7) methane (CH_4) and nitrous oxide (N_2O) emissions were estimated for 2020 from enteric fermentation and manure management of cattle, sheep, and goats in Republic of Kazakhstan. The results are summarized in Table 5.

As shown in Table 5, methane emissions in Republic of Kazakhstan in 2020 totaled 594,426.58 tons, equivalent to 13.67 million tons of CO_2-eq. per year (global warming potential ×28). Given that 1 m^3 of methane provides 6.5–9.5 kWh of energy and up to 11,000 kcal/m^3, this renewable source has strong potential for heat and power generation. Studies confirm that large livestock farms can cover up to 80–85% of their energy needs through waste utilization.

Table 5

Calculation of methane emissions from enteric fermentation and manure for 2020 in Republic of Kazakhstan

Animal type	Number of animals ($N_{livestock}$)	Coefficient emissions from enteric fermentation (EF, kg/livestock year)	Emission from enteric fermentation (Emissions CH_4, kg/year)	Coefficient emissions from manure (EF(AWMS), kg/livestock year)	Emissions from manure (*Nex*(*T*), kg CH_4 year)	Total emissions from animals (N_2O(*AWMS*), CH_4)
Cows, dairy cattle	4,026,977	56	225,510,712	4.6	18,524.09	244,034.81
Cattle (meat, sires, etc.)	3,954,161	44	173,983,084	2.64	10,438.99	175,026.98
Sheeps	18,959,523	8	151,676,184	1.2	22,751.43	153,951.33
Goats	2,436,246	8	19,489,968	1.2	29,234.95	22,413.46
Total	–	–	570,659,948	–	24,766,631	594,426.58

5. 2. Potential of biogas production from organic waste

With biogas containing ~70% CH_4, 1 m^3 can generate 2–3 kW of electricity [26]. Thus, methane released in 2020 could theoretically produce over 2.2 billion kW of electric energy, representing untapped potential for Republic of Kazakhstan.

However, according to the Environmental Code of Republic of Kazakhstan, GHG emissions are excluded from public environmental expertise (clause 60) and audit analysis (clause 80). CO_2 from livestock is not assessed since annual balances are considered neutral-absorbed by plants and returned through respiration.

Methane and nitrous oxide, however, must be evaluated separately, as they result from enteric fermentation and manure decomposition. The proposed technology focuses on processing these emissions into biogas, simultaneously producing thermal and electric energy while reducing environmental impact. Fig. 2 depicts the obtaining of the biogas systems and its each wing deals.

In 2020, methane emissions in Republic of Kazakhstan reached 594,426.58 tons, equal to 13.67 million tons of CO_2-eq. (GWP ×28). With an energy value of 6.5–9.5 kWh/m^3 and up to 11,000 kcal/m^3, methane represents a significant renewable resource. Studies show that livestock farms can meet 80–85% of their energy demand through waste utilization.

Since biogas (~70% CH_4) can generate 2–3 kW per m^3 [27–29], 2020 emissions alone could yield over 2.2 billion kW of electricity – an untapped potential for Republic of Kazakhstan. Yet, under the Environmental Code, GHG emissions are excluded from expertise and audit, while livestock CO_2 is treated as neutral.

Unlike CO_2, methane and nitrous oxide require separate assessment. Their capture and conversion into biogas could both supply energy and reduce environmental impacts.

6. Discussion of greenhouse gas mitigation strategies in livestock farming

The results obtained (Table 5) show that methane emissions from livestock farming in the Republic of Kazakhstan in 2020 totaled 594,426.58 tons, corresponding to 13.67 million tons CO_2-eq. (GWP × 28). This value, derived from enteric fermentation and manure management of cattle, sheep, and goats, highlights livestock farming as a major contributor to the national greenhouse gas (GHG) inventory. Given the energy potential of methane (6.5–9.5 kWh per m^3 and up to 11,000 kcal/m^3), the emissions correspond to a theoretical energy potential of more than 2.2 billion kWh per year, confirming the substantial renewable energy capacity embedded in livestock waste. The technological scheme (Fig. 2) consists of sequential modules – manure collection, anaerobic digestion, biogas purification, cogeneration, and digestate utilization – forming a closed-loop system. Methane generated during digestion is captured and converted into heat and electricity, while the remaining digestate is used as an organic fertilizer. This structure ensures simultaneous mitigation of GHG emissions and renewable energy generation, confirming the practical biogas potential embedded in livestock waste management systems.

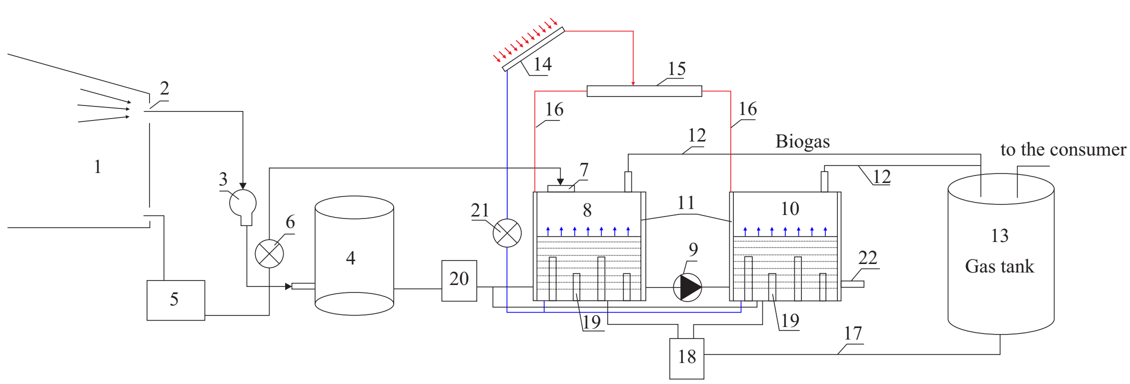

Fig. 2. Technological scheme of the method of obtaining biogas and environmentally friendly organic fertilizer:
1 — livestock room; 2 — channel for gas-air mixture; 3 — suction pump; 4 — tank for gas-air mixture; 5 —tank for accumulation of organic waste; 6 — pump for pumping organic waste; 7 — intake neck for organic waste; 8 — bioreactor operating in mesophilic mode; 9 — centrifugal pump; 10 — bioreactor operating in thermophilic mode; 11 — water jacket of bioreactors; 12 — pipeline for pumping biogas into a gas tank; 13 — gas tank; 14 — solar collector; 15 — storage tank for heated water; 16 — supply pipes for supplying heated water to the bioreactor water jackets; 17 — a pipe for supplying biogas to an autonomous boiler; 18 — an autonomous universal boiler; 19 — a tube for supplying a gas-air mixture to bioreactors; 20 — a compressor; 21 — a water pump for pumping water into a solar collector; 22 — a tap for draining finished organic fertilizer

The results obtained are consistent with the national inventory data of the Republic of Kazakhstan, but exceed some regional estimates reported in independent studies. This difference is primarily explained by local environmental factors, livestock density, and manure management practices, which significantly affect methane formation rates.

In comparison with conventional manure storage or partial anaerobic digestion [10, 12], the proposed integrated biogas system considers both manure management and energy recovery, thus providing a dual environmental and energy benefit. Similar international studies [14–16] report that livestock enterprises can meet 80–85% of their total energy demand through waste utilization, a result confirmed by theoretical calculations for Republic of Kazakhstan. Furthermore, the approach aligns with circular economy principles, enhancing resource efficiency in agriculture and contributing to the country's decarbonization goals.

Methodological constraints: Emission estimates rely on inventory-based formulas rather than on direct instrumental measurements, which introduces uncertainty associated with emission factors and activity data defined by the IPCC methodology.

Applicability limits: The feasibility of biogas technologies depends on farm scale, climatic conditions, and the continuity of manure supply. In small or nomadic livestock systems typical of some regions of Kazakhstan, these factors may reduce the efficiency of energy recovery.

Reproducibility and stability: The reproducibility of the calculated energy potential assumes constant manure collection and digestion parameters, which are difficult to maintain under real field conditions.

A number of disadvantages are inherent in this research. The current study does not include a detailed techno-economic analysis of biogas plant implementation and lacks a social assessment of farmers' readiness to adopt new technologies. In addition, infrastructure and policy barriers such as the exclusion of GHG emissions from public environmental expertise and audit (Environmental Code, clauses 60 and 80) hinder the practical application of the results.

To overcome these shortcomings, future work should incorporate pilot-scale demonstrations, cost-benefit assessments, and socio-economic surveys to evaluate adoption potential and regional scaling.

Further research should focus on experimental validation of methane capture efficiency and biogas conversion rates under local climatic conditions. Mathematical modeling of integrated emission reduction and energy generation scenarios can refine the national potential for GHG mitigation.

However, several challenges may arise, including:

– maintaining stable anaerobic digestion performance in low-temperature environments;

– ensuring long-term monitoring of methane and nitrous oxide fluxes;

– developing robust methodologies for assessing emission reductions with high reproducibility.

Addressing these issues will support the creation of scalable, energy-efficient, and environmentally sustainable livestock farming systems in Republic of Kazakhstan.

From an environmental perspective, methane and nitrous oxide emissions must be assessed separately from carbon dioxide, since unlike CO_2, they are not neutralized in annual natural cycles. Their capture and conversion into biogas provide dual benefits:

– reducing GHG emissions from agriculture, thereby contributing to climate change mitigation;

– producing renewable energy and organic fertilizers, which can substitute fossil fuels and mineral fertilizers, improving sustainability in the agricultural sector.

However, Republic of Kazakhstan Environmental Code currently excludes GHG emissions from public environmental expertise (clause 60) and audit analysis (clause 80). This regulatory gap limits systematic monitoring and mitigation of methane and nitrous oxide in livestock farming. Integrating biogas technologies could close this gap by providing both energy independence for farms and improved environmental performance.

7. Conclusions

1. Quantitative assessment of methane and nitrous oxide emissions from livestock in Republic of Kazakhstan showed that in 2020 methane emissions reached 594,426.58 tons (13.67 million tons CO_2-eq., GWP ×28). This confirms that enteric fermentation and manure management are the dominant sources of agricultural GHGs (58% CH_4, 42% N_2O), which differs from earlier estimates by providing more detailed livestock-specific calculations. The obtained values explain the scale of the environmental burden and justify the urgency of emission mitigation.

2. Evaluation of the biogas potential demonstrated that methane released in 2020 could yield over 2.2 billion kW of electricity, given the energy content of 6.5–9.5 kWh/m^3. Compared to earlier studies, this result quantifies the renewable energy potential for Kazakhstan's conditions and shows that large livestock farms could cover 80–85% of their own energy needs. This highlights the practical feasibility of replacing fossil fuels with biogas, explaining the advantage of integrating such systems.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this study, whether financial, personal, authorship or otherwise, that could affect the study and its results presented in this paper.

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Data availability

Manuscript has data included as electronic supplementary material.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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