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The Strategic Importance of Biogas Technology in Sustainable Livestock Farming: Perspectives on Energy, Environment, and Rural Development

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Abstract

Sustainable livestock farming is regarded as an important research area in terms of reducing environmental impacts, ensuring efficient resource use, and supporting rural development. In this context, biogas technology provides significant environmental and economic benefits by converting animal manure and agricultural by-products into renewable energy. The use of biogas produced through anaerobic fermentation for electricity and heat generation enables livestock enterprises to meet part of their energy needs while reducing their dependence on fossil fuels. The digestate generated as a by-product of the process can also be utilised as organic fertiliser, contributing to the recycling of nutrients in agricultural production. Thus, the conversion of waste into valuable resources, the recovery of nutrients, and improved resource efficiency enable the practical implementation of the circular economy approach. This study examines the role of biogas technology in sustainable livestock farming systems from the perspectives of energy production, reduction of environmental pressures, and economic sustainability. Particular attention is given to the contribution of biogas applications to reducing energy costs, limiting fossil fuel consumption, and utilising local renewable energy resources, particularly in small- and medium-scale livestock enterprises. In conclusion, biogas technology is considered an important tool that integrates animal waste management with energy production, supports environmental sustainability, and contributes to strengthening the economic resilience of rural communities.

Cite

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1. INTRODUCTION

The modern development of livestock farming has led to an increase in the volume of organic waste, particularly manure from cattle, pigs, and poultry. In the absence of an effective waste management system, manure becomes a source of greenhouse gas emissions, surface and groundwater pollution, unpleasant odours, nitrogen and phosphorus losses, as well as sanitary and environmental risks. At the same time, manure contains considerable energy and resource potential that can be utilised within the framework of the circular economy concept (Khoshnevisan et al., 2021). Under current conditions, therefore, there is a shift from the traditional perception of manure as waste toward its recognition as a secondary raw material for the production of energy, fertilisers, and other value-added products.

One of the most mature technologies for the energy recovery of livestock waste is anaerobic digestion. During anaerobic digestion, organic matter is decomposed by a complex of microorganisms under oxygen-free conditions, producing biogas, whose main energy component is methane. Recent studies consider biogas not only as an alternative fuel but also as an energy vector that can be integrated into systems for heat and electricity generation and the production of purified biomethane (Rafiee et al., 2021).

Systematic studies conducted recently demonstrate a sustained increase in scientific interest in the use of livestock manure for biogas production. In particular, a recent review based on a Scopus search using the keywords 'biogas' and 'livestock manure' identified extensive research activity focused on optimising biogas production, assessing environmental and socio-economic impacts, and evaluating the economic viability of biogas systems (Brahmi et al., 2024).

However, the energy value of the technology represents only one component of its strategic importance. Anaerobic digestion simultaneously enables the stabilisation of organic matter, reduction of the volume of potentially polluting waste, and production of digestate containing nitrogen, phosphorus, potassium, and organic matter. It is precisely this combination of energy recovery and material recycling that makes biogas technology particularly important for circular agriculture (Awasthi et al., 2022; Samoraj et al., 2022).

The aim of this review is to systematise current scientific understanding of the strategic role of biogas technologies in sustainable livestock farming by considering them through four interconnected dimensions: energy security, environmental sustainability, resource recycling, and socio-economic development of rural areas.

2. LITERATURE REVIEW METHODOLOGY

Publications from 2020 to 2026 focusing on anaerobic digestion of livestock manure, biogas production, digestate utilisation, life cycle assessment, techno-economic performance, environmental impacts, and rural development were used to prepare this review.

The main thematic search combinations included: biogas, livestock manure, animal manure, anaerobic digestion, livestock farming, digestate, renewable energy, circular economy, life cycle assessment, and rural development. Priority was given to articles and review papers published in international peer-reviewed journals indexed in Scopus.

The literature was grouped into the following thematic blocks:

- anaerobic digestion technologies and enhancement of methane yield;
- energy utilisation of biogas;
- environmental impacts and emission reduction;
- digestate and nutrient recovery;
- techno-economic and LCA assessment;
- biogas as a tool for rural development;
- prospects for small- and medium-sized livestock enterprises.

This approach makes it possible to consider biogas technology not merely as a method for methane production but as an element of an integrated production and energy system.

3. ANAEROBIC DIGESTION OF LIVESTOCK WASTE AS THE BASIS OF BIOGAS TECHNOLOGY

Anaerobic digestion is a sequence of biochemical stages that includes hydrolysis, acidogenesis, acetogenesis, and methanogenesis. Different functional groups of microorganisms participate at each stage; therefore, process stability depends on temperature, pH, dry matter content, organic loading rate, retention time, carbon-to-nitrogen ratio, and substrate composition.

The review by Obileke et al. (2021) shows that temperature is one of the most important factors determining microbial activity and the rate of biogas production. Maintaining a stable temperature regime is particularly important for farms operating under mesophilic or thermophilic digestion conditions.

For cattle manure, an additional challenge is the presence of lignocellulosic components. These components are relatively difficult to hydrolyse, resulting in part of the organic matter remaining unused. Li et al. (2021) noted that the low accessibility of the lignocellulosic fraction is one of the limiting factors for achieving high methane yields from cattle manure.

One approach to addressing this problem is substrate pretreatment. Khan and Ahring (2021) demonstrated that alkaline-thermal pretreatment can substantially enhance the degradation of the recalcitrant fraction of manure; under the conditions investigated, the addition of NaOH significantly increased methane yield.

Another approach is co-digestion. The combined processing of manure with crop residues, food waste, or other organic substrates can improve the C/N ratio, increase the availability of organic matter, and enhance methane production. A meta-analysis of the anaerobic co-digestion of manure demonstrated a pronounced synergistic effect at an optimal ratio of components, with a C/N range of approximately 20-27 considered favourable for co-digestion in the systems investigated (Zhou et al., 2021).

Experimental studies further confirm the importance of substrate composition. Wei et al. (2021), in the co-digestion of chicken manure and corn straw, showed that substrate modification and the addition of trace elements can increase biomethane yield while simultaneously altering the structure of the microbial community.

High-solids anaerobic digestion is also considered a promising technology for farms where the transportation of large volumes of liquid material is economically impractical. Abid et al. (2021) demonstrated that increasing the dry matter content to a certain level is possible without compromising process stability, although further increases in concentration can intensify hydrolysis limitations (Fig. 1).

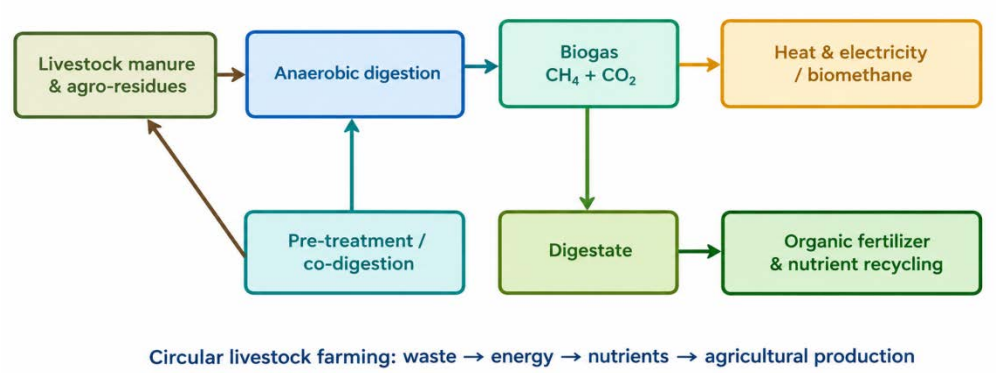


Fig. 1. *Biogas pathway from livestock manure to energy and nutrient recycling* (*Khoshnevisan et al. 2021; Tampio et al. 2024*)

Thus, modern anaerobic digestion technology is gradually evolving from a simple manure treatment process into a more sophisticated biorefinery system in which methane production, digestate quality, and the overall material balance of the farm are optimised simultaneously.

4. BIOGAS AS A TOOL FOR ENHANCING THE ENERGY SUSTAINABILITY OF LIVESTOCK ENTERPRISES

The key strategic advantage of biogas technology lies in its ability to convert organic waste into a local source of energy. The biogas produced can be used directly for heat generation, in combined heat and power (CHP) units for the simultaneous production of electricity and heat, or, after purification and upgrading, in the form of biomethane.

Rafiee et al. (2021) consider biogas a versatile energy carrier because it can be integrated with various energy technologies and used for multiple end-use applications. At the same time, the composition of the feedstock and the purification technology determine the quality of the final gas and its potential applications.

For livestock enterprises, the possibility of using the generated energy directly within the farm is particularly important. Thermal energy can be used for heating facilities, hot water production, and maintaining the operating temperature of the digester. Electricity can be used to power pumps, ventilation systems, lighting, cooling systems, and other equipment.

This approach reduces the need to purchase electricity and fuel from external sources. Consequently, a biogas plant becomes not merely a waste management system but an integral part of the farm's energy infrastructure.

The importance of this approach is particularly evident for small and medium-sized enterprises located far from major energy grids. Brahmi et al. (2024) note that the development of small- and medium-scale biogas plants can simultaneously address waste management, energy production, and improved energy accessibility in rural areas.

Recent studies indicate that energy integration can be extended beyond conventional electricity generation. For example, Saka and Orhan (2025) investigated the use of biogas for absorption cooling in rural areas of Turkey. The authors demonstrated that such a system can be adapted to the needs of small and medium-sized farms, including the provision of cooling and agricultural product storage.

A particularly promising area is the use of biogas as part of distributed energy systems. Naranjo Herrera et al. (2026), studying electricity generation from cattle and pig manure on small farms in Brazil, demonstrated the economic attractiveness of decentralised generation. In the scenarios examined, distributed systems could be up to 38.5% more profitable than individual systems, while the use of digestate as a biofertiliser further improved the economic performance.

THUS, THE ENERGY FUNCTION OF BIOGAS SHOULD BE ASSESSED NOT ONLY IN TERMS OF THE AMOUNT OF GAS PRODUCED BUT ALSO IN TERMS OF THE EXTENT TO WHICH IT REPLACES EXTERNALLY SUPPLIED ENERGY RESOURCES.

5. BIOGAS AND THE REDUCTION OF THE ENVIRONMENTAL BURDEN OF LIVESTOCK FARMING

One of the main environmental benefits of anaerobic digestion is the controlled treatment of organic matter, which under conventional storage conditions can become a source of methane and other pollutants.

Khoshnevisan et al. (2021) emphasise that improper manure management is associated with numerous environmental risks, whereas anaerobic digestion can simultaneously reduce the organic load and generate renewable energy.

However, the environmental effect of biogas technology is not automatically positive. It depends on how effectively methane leakage, digestate storage, substrate transportation, and the use of the generated energy are controlled.

In a comparative LCA analysis of mono- and co-digestion of manure, Hossain et al. (2023) showed that co-digestion with organic waste can substantially reduce climate impacts and certain other environmental impacts. At the same time, open storage of digestate was identified as one of the major sources of environmental burden.

This is a fundamentally important consideration: the construction of a biogas plant alone does not guarantee environmental sustainability. It is necessary to ensure the tightness of the digester, gas holder, and digestate storage system, as well as the rational utilisation of the final products.

In an LCA analysis of a biogas plant on a pig farm, Freitas et al. (2022) demonstrated that the outcome depends on the selected co-digestion scheme and the use of additional substrates. Additional energy production may be associated with environmental costs if the supplementary crops require significant amounts of fossil fuels for cultivation and transportation.

Balcioglu et al. (2022) also demonstrated the need for an integrated consideration of environmental and economic factors when assessing energy production from organic waste. Anaerobic digestion simultaneously serves the functions of energy supply, waste treatment, and organic fertiliser production; therefore, its performance should be evaluated based on the overall range of impacts rather than a single indicator.

6. DIGESTATE AS A KEY ELEMENT OF THE CIRCULAR ECONOMY

One of the main advantages of anaerobic digestion compared with simple combustion or other energy technologies is the retention of a significant proportion of nutrients in the final product digestate.

Digestate contains nitrogen, phosphorus, potassium, and organic matter and can therefore be returned to the agricultural cycle. Samoraj et al. (2022) consider digestate a potential component of nutrient management systems, highlighting the possibility of using both its liquid and solid fractions in agriculture. At the same time, salinity, phytotoxicity, and sanitary parameters need to be carefully controlled.

A recent review by Sobhi et al. (2024) shows that the use of digestate as an organic fertiliser has considerable potential, but it also requires monitoring of heavy metals, pathogens, excessive nutrient application, microplastics, and other contaminants.

Therefore, the concept of "waste → biogas" is incomplete. A more appropriate representation is the following system:

manure → biogas → energy + digestate → fertiliser → crop production → feed → livestock farming.

It is precisely this closed-loop chain that corresponds to the principles of the circular economy.

Tampio et al. (2024) demonstrated that the co-digestion of manure with carbon-rich substrates, such as straw, affects not only methane production but also carbon stabilisation in digestate. According to the modelling results, approximately 22% of the initial carbon could contribute to the formation of soil organic carbon stocks following digestate application.

Thus, the application of digestate can generate additional environmental value from the biogas process by increasing the return of organic matter to the soil.

7. TECHNOLOGICAL APPROACHES TO INCREASING BIOGAS YIELD

Recent literature identifies several key strategies for improving the efficiency of biogas plants:

7.1. Pretreatment

Pretreatment is designed to break down the complex structure of organic matter and increase its availability to microorganisms. Khan and Ahring (2021) demonstrated the effectiveness of alkaline-thermal treatment for the treatment of a recalcitrant manure fraction. Kim et al. (2023) also demonstrated that thermal hydrolysis can increase the biochemical methane potential and energy yield during the treatment of cattle manure.

7.2. Co-digestion

The combined treatment of manure with food and plant residues can improve substrate composition and increase energy yield. Hossain et al. (2023) showed that the co-digestion of manure with food waste can provide substantial environmental benefits compared with separate treatment scenarios.

More recent studies confirm the potential of industrial-scale co-digestion. Enokida et al. (2025) investigated the co-digestion of livestock manure with various agro-industrial wastes in a CSTR reactor and demonstrated the potential to improve process stability and biogas production.

7.3. Use of Additives

The addition of certain mineral and carbon-based materials can influence microbial activity, process stability, and methane yield. Liu et al. (2021) noted that the effectiveness of additives depends on the type of substrate, dosage, and specific conditions of the anaerobic process.

Yun et al. (2023) proposed a comprehensive assessment system that considers not only energy production but also process stability, substrate degradation efficiency, and digestate quality and safety. This approach is important for moving from an assessment based solely on methane yield toward an evaluation of the overall performance of the biogas system.

8. ECONOMIC SUSTAINABILITY OF BIOGAS SYSTEMS

Economic efficiency is one of the key factors determining the practical adoption of biogas plants. Even an environmentally efficient technology may be economically unattractive when capital costs are high, reactor loading is low, or there is no established market for digestate.

Awasthi et al. (2022) indicate that the main barriers to the development of livestock manure treatment systems include initial investment costs, operating expenses, manure collection logistics, and subsequent digestate management. The authors emphasise the need to integrate energy production, nutrient recovery, and viable business models.

Agar et al. (2022) showed that the economic attractiveness of electricity generated from biogas should be assessed by considering the value of avoided emissions, electricity tariffs, and the specific characteristics of rural areas. Therefore, economic support mechanisms, including subsidies, concessional financing, and guaranteed tariffs, are necessary for some regions.

The example of a large-scale biogas plant in Nepal is particularly illustrative. Cheng et al. (2024) found that the actual loading and efficiency indicators of the plant may differ substantially from the design values. Although the facility retained environmental benefits, its financial viability under actual operating conditions was considerably lower than initially estimated.

This demonstrates that a techno-economic assessment should be based not on the design capacity but on realistic operational performance.

A decentralised model is particularly promising. Naranjo Herrera et al. (2026) showed that small-scale manure-to-electricity systems can be economically attractive, especially when the generated energy and digestate are used locally.

9. THE IMPORTANCE OF BIOGAS FOR SMALL AND MEDIUM-SIZED LIVESTOCK FARMS

For large livestock complexes, the construction of a biogas plant can be financed through their own capital and supported by large volumes of feedstock. However, for small and medium-sized farms, the main advantage may be precisely a modular and decentralised system.

Such enterprises have several distinctive characteristics:

- relatively small volumes of manure;
- limited access to capital;
- high sensitivity to electricity and fuel costs;
- the need to reduce waste disposal costs;
- the possibility of directly using heat and electricity;
- potential demand for organic fertilisers.

Brahmi et al. (2024) emphasise the particular importance of small- and medium-scale biogas plants in rural communities, as local energy production can reduce transportation costs while simultaneously creating additional economic activity.

From an organisational perspective, a cooperative model may be the most rational approach. Several farms can combine their manure resources and jointly operate a biogas plant. This makes it possible to increase the substrate volume, ensure stable reactor loading, and reduce specific capital costs.

Such a model is particularly promising for regions with a high concentration of livestock farms and underdeveloped infrastructure for the processing of organic waste.

10. BIOGAS AND RURAL DEVELOPMENT

The strategic importance of biogas technology extends beyond an individual farm. When scaled up, biogas systems can create new value chains:

livestock farming → manure collection → biogas plant → energy → digestate processing → fertiliser → crop production → feed → livestock farming.

As a result, a local circular economy is established.

Brahmi et al. (2024) associate the development of biogas enterprises with the reduction of energy poverty, improved access to renewable energy, and the development of rural communities.

Saka and Orhan (2025) showed that biogas can be used not only for electricity generation but also for agricultural cooling. This is particularly important in regions where inadequate refrigeration infrastructure leads to losses of agricultural products (Fig. 2).

Thus, biogas technology has the potential to contribute to:

- the creation of new jobs;
- the development of local energy markets;
- the reduction of farm operating costs;
- increased energy independence;
- improved sanitary conditions in rural areas;
- the development of the organic fertiliser market;
- reduced environmental pressures;
- increased resilience of agriculture to rising fossil fuel prices.

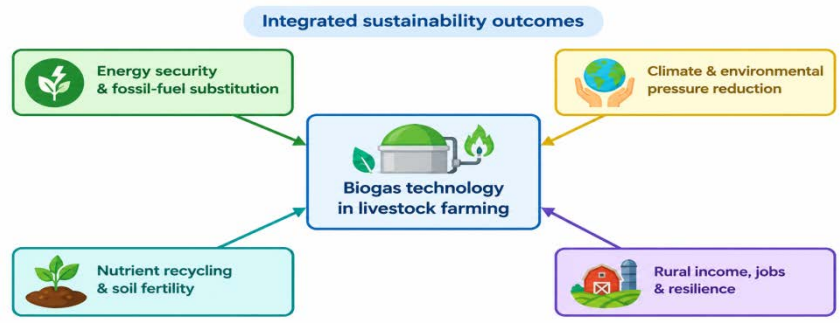


Fig. 2. *Integrated sustainability benefits of biogas technology in livestock farming.* (Brahmi et al. 2024; Awasthi et al. 2022)

11. CURRENT TRENDS IN TECHNOLOGY DEVELOPMENT

Based on the studies reviewed, several major directions for further development can be identified.

11.1. Transition from Biogas to Biomethane

Purification of biogas from CO_2, H_2S, moisture, and other impurities makes it possible to produce biomethane suitable for a wider range of energy applications. Rafiee et al. (2021) consider biogas purification and upgrading technologies to be one of the key elements in establishing a comprehensive biogas utilisation chain.

11.2. Integration with Other Technologies

Modern biogas plants are increasingly being considered as components of biorefineries. Anaerobic digestion can be combined with the production of organic fertilisers, nitrogen and phosphorus recovery, biochar production, hydrogen generation, and other products.

Tehseen et al. (2026) proposed an integrated system in which manure is used for biogas production, followed by hydrogen and biofertiliser production. The model reduced the global warming potential by 66% per unit of dairy production while maintaining milk productivity.

11.3. Digitalisation

A promising direction is the implementation of sensors and automated systems for monitoring temperature, pH, pressure, gas composition, and organic loading. This can improve process stability and reduce the risk of disturbances in methanogenesis.

11.4. Regional Optimisation

No single technological configuration can be considered universally applicable to all farms. The optimal option depends on climate, animal species, dry matter content of manure, availability of crop residues, electricity costs, transportation distances, and opportunities for digestate utilisation.

Therefore, regional techno-economic modelling of biogas systems represents a particularly promising direction.

12. COMPARATIVE ANALYSIS OF THE MAIN ADVANTAGES AND LIMITATIONS

Biogas technology provides a range of environmental, energy, economic, and agricultural benefits within sustainable livestock farming systems. At the same time, its practical implementation is associated with several technical, financial, and organisational challenges that may vary depending on farm size and available feedstock resources. The main potential advantages and limitations of biogas production across key areas of sustainable livestock farming are summarised in Table 1.

Table 1. Potential Advantages and Main Limitations of Biogas Technologies in Sustainable Livestock Farming

Area	Potential Advantage	Main Limitation
Energy	Heat and electricity production	Energy output depends on substrate quality
Waste Management	Stabilisation of organic matter	Requires organised manure collection
Climate	Reduction of uncontrolled methane emissions	Risk of CH_4 leakage

Area	Potential Advantage	Main Limitation
Fertilisers	Production of digestate	Potential accumulation of contaminants
Circular Economy	Recovery of N, P, K, and organic matter	A market for digestate is required
Economics	Reduction in energy costs	High initial investment costs
Rural Development	Job creation and local energy production	Financial and institutional support mechanisms are required
Small Farms	Decentralised energy supply	Small feedstock volumes
Large Farms	High energy potential	Complex management and high equipment costs

Thus, biogas technology is most effective when feedstock, energy utilization, digestate management, and the economic model are optimized simultaneously.

13. PROSPECTS FOR APPLICATION IN CENTRAL ASIAN CONDITIONS

The development of biogas technologies is of particular interest for Central Asian countries due to the combination of rapidly developing livestock farming, the need to improve the energy resilience of rural areas, and the availability of large amounts of organic waste.

In rural areas of Kazakhstan, Uzbekistan, Kyrgyzstan, and other countries in the region, small- and medium-scale plants operating directly at livestock farms or jointly serving several farms appear to be the most promising options.

A particularly promising scheme is:

Livestock manure + crop residues → anaerobic digestion → biogas → heat/electricity → digestate → organic fertiliser → crop production.

For regions with well-developed crop production, an additional advantage is the possibility of co-digesting manure with straw, crop residues, and other agricultural wastes.

At the same time, the transfer of foreign technological solutions should take into account local climatic conditions, water availability, temperature regimes, the structure of rural settlements, and the cost of energy resources. It is particularly important to conduct a preliminary assessment of the available quantity of manure and the seasonal stability of its supply.

14. DISCUSSION

A synthesis of recent publications shows that the strategic value of biogas technology lies not in methane production alone, but in its ability to address several challenges simultaneously.

First, biogas enables livestock waste to be converted into an energy resource. Second, anaerobic digestion helps reduce environmental risks associated with conventional manure storage. Third, the retention of nutrients in digestate creates an opportunity to return valuable resources to crop production. Fourth, local energy production can strengthen the economic resilience of farms.

However, the literature also shows that the overall effect depends on the quality of management of the entire system. Hossain et al. (2023) identified the importance of digestate storage for the

environmental balance, while Cheng et al. (2024) demonstrated that the actual performance of large-scale biogas plants can fall substantially below their design values.

Therefore, from a strategic perspective, the goal should not simply be to construct the maximum possible number of biogas plants but rather to develop region-specific systems in which feedstock availability, plant capacity, energy utilisation, and digestate management are mutually coordinated.

The integration of biogas plants with other components of circular agriculture is particularly promising. In this case, the farm becomes not merely an end consumer of resources but part of a closed-loop production system.

15. CONCLUSION

An analysis of recent scientific research in the field of biogas technologies allows the following conclusions to be drawn:

- Anaerobic digestion is one of the most promising technologies for livestock manure management, as it can simultaneously address waste management and renewable energy production.
- The energy potential of biogas extends beyond electricity generation. Biogas can be used for heat production, combined heat and power generation, cooling, and, after purification, as biomethane.
- The environmental benefits of biogas technology depend on the quality of system management. The most important factors include preventing methane leakage, proper digestate storage, minimising transportation distances, and rational energy utilisation.
- Co-digestion and pretreatment are key approaches for improving biogas production efficiency, particularly when processing poorly degradable manure.
- Digestate is not a waste product but a secondary resource that can return nitrogen, phosphorus, potassium, and organic matter to the agricultural cycle. However, its application requires monitoring of sanitary and chemical parameters.
- The economic efficiency of biogas plants is determined not only by the amount of biogas produced but also by capital investment costs, operating expenses, the possibility of utilising heat and electricity locally, and the value of the fertiliser product.
- For small- and medium-sized livestock enterprises, decentralised and cooperative models are the most promising, as they allow the feedstock resources of several farms to be combined and energy to be used directly in rural areas.
- A current development trend is the transition from the traditional "manure → biogas" model to an integrated "waste → energy → fertiliser → crop production → livestock farming" model, consistent with the principles of the circular economy.
- Recent studies published in 2026 indicate a further expansion of this concept toward multifunctional biorefinery systems, in which manure can serve as a source not only of biogas and fertilisers but also of hydrogen and other value-added products.

Overall, biogas production technology can be regarded as a strategic component of sustainable livestock farming, integrating energy security, environmentally sound waste management, nutrient recovery, and rural development. Its further expansion requires not only technological improvements but also comprehensive government policies, financial support mechanisms, regional planning, and the development of markets for biogas-derived products.

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