ECOLOGY

UDC 631.171
DOI: 10.15587/1729-4061.2025.323371

IMPROVEMENT OF TECHNOLOGY OF BIOLOGICAL PURIFICATION OF WASTE FROM SHEEP FARMS

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The research focuses on developing and improving biological treatment technologies for agricultural waste to address environmental challenges and enhance sustainability. The object of the study includes various types of agricultural waste, such as crop residues, livestock manure, and processing by-products, which often contribute to pollution and inefficient resource utilization when poorly managed. The primary problem addressed is the need for effective and eco-friendly solutions to mitigate the environmental impact of agricultural waste while maximizing its potential as a resource. Advanced algorithms for optimizing the efficiency and forecasting of energy production have been developed, which have made it possible to achieve a prediction accuracy of 85 %. The combined system has demonstrated a 30 % increase in energy stability compared to using a single renewable source. Adaptive control mechanisms and efficient energy storage management have reduced energy losses in adverse weather conditions by 20 %. These results confirmed the hybrid system's ability to provide stable electricity, reduce dependence on fossil fuels by up to 40 %, and reduce CO_2 emissions by about 25 %.

The study explained these results by demonstrating the synergistic effects of microbial consortia and tailored treatment conditions on waste breakdown and nutrient transformation. Key features of the results include their scalability, cost-effectiveness, and adaptability to different types of agricultural waste. These characteristics allowed the technology to address the problem of inefficient waste management comprehensively

Keywords: biological treatment, agricultural waste, microorganisms, biofertilizers, biogas, organic farming, waste management, sustainable agriculture

Received 10.02.2025
Received in revised form 31.03.2025
Accepted 18.04.2025
Published

***How to Cite:** Baimukhanbetov, A., Bakhtiyar, B., Tokmoldayev, A., Kassym, R., Tursunbayeva, G., Korobkov, M., Sharipov, T., Manapova, G., Mergalimova, A., Saparov, D. (2025). Improvement of technology of biological purification of waste from sheep farms. Eastern-European Journal of Enterprise Technologies, 2 (10 (134)), 6–13. https://doi.org/10.15587/1729-4061.2025.323371*

1. Introduction

The sustainable management of agricultural waste is an increasingly pressing issue in the modern era due to its economic, and social implications. Agricultural activities generate vast quantities of organic waste, including crop residues, animal manure, and food processing by-products. When improperly managed, these wastes can lead to environmental pollution, such as water contamination, greenhouse gas emissions, and soil degradation. Moreover, the inefficient use of agricultural waste represents a missed opportunity to recover valuable resources, such as nutrients and energy, which could otherwise contribute to sustainable farming practices [1].

Current global challenges, such as climate change, resource scarcity, and the demand for sustainable food production systems, underscore the importance of addressing agricultural waste management. Traditional methods, such as landfilling or incineration, are increasingly recognized as unsustainable due to their environmental impacts and high costs. Chemical treatments, while effective in some cases, may introduce harmful residues into the ecosystem and are often economically infeasible for small-scale farmers.

In this context, biological treatment technologies offer a promising alternative. By leveraging natural microbial processes, agricultural waste can be transformed into valuable products such as biofertilizers, biogas, and organic soil amendments. These technologies not only mitigate environmental impacts but also contribute to circular agricultural practices by recycling nutrients and reducing dependence on synthetic inputs [2]. Furthermore, advances in microbiology and bioengineering have created opportunities to enhance the efficiency and scalability of these methods, making them increasingly accessible to diverse agricultural operations worldwide.

Given the growing need for sustainable waste management solutions, the development and optimization of biological treatment technologies remain highly relevant. Research in this area is essential to address existing gaps, improve treatment efficiency, and adapt these methods to varying agricultural and environmental conditions.

Therefore, the scientific explorations and advancement of biological treatment technologies for agricultural waste are highly relevant and necessary to meet the challenges of sustainable agriculture and environmental conservation [3].

2. Literature review and problem statement

The paper [4] presents the results of research on the application of advanced microbial consortia for biogas enhancement. The study demonstrated that microbial optimization significantly improves biogas yield by enhancing substrate breakdown efficiency. It is shown that the application of engineered microbial consortia increased methane production rates. However, unresolved issues remain regarding the long-term stability of microbial communities under variable feedstock conditions. The reason for this may be objective difficulties associated with maintaining an optimal microbial balance, which fluctuates due to changes in environmental conditions and substrate variability. A way to overcome these difficulties can be the development of adaptive microbial control strategies.

In [5], the authors examined advanced strategies for sustainable waste-to-energy systems in agriculture. The study provided valuable insights into the integration of anaerobic digestion with other renewable energy sources to maximize sustainability. However, there were unresolved issues related to the efficiency of large-scale implementation and the economic feasibility of these systems. The cost part in terms of infrastructure and operational expenses makes large-scale application impractical in certain regions. A way to overcome these limitations can be the optimization of process parameters and the integration of artificial intelligence for predictive control of digestion efficiency.

The research in [6] explored biogas upgrading and utilization, focusing on current methods of methane purification and storage. It is shown that existing upgrading technologies, such as membrane separation and pressure swing adsorption, improve biogas purity. But there were unresolved issues related to the high energy demand and cost-intensive nature of these processes. The reason for this may be the fundamental impossibility of achieving high-purity biogas without incurring significant energy expenditures. A way to overcome these challenges can be the development of low-energy purification technologies using bio-based methods, such as enzymatic purification or microbial electrochemical cells.

Paper [7] discusses the opportunities associated with biogas utilization in various sectors. The study highlighted the potential of biogas as a replacement for fossil fuels, particularly in decentralized energy systems. However, unresolved issues include the seasonal variation in feedstock availability, which affects biogas production consistency. The reason for this may be the fundamental dependence of biogas production on agricultural waste cycles, making stable year-round production difficult. A way to mitigate this issue could be the development of hybrid energy systems that integrate biogas with other renewable energy sources, ensuring continuous energy availability.

In [8], the focus was on optimizing microbial communities for sustainable anaerobic digestion. It is shown that targeted microbial engineering improves process efficiency and methane yield. However, unresolved challenges remain regarding the adaptability of engineered microbes to fluctuating environmental conditions. The reason for this may be the limited ability of synthetic microbial consortia to cope with real-world variations in temperature, pH, and substrate composition. A way to overcome these difficulties can be the implementation of real-time monitoring and adaptive microbial management techniques.

The study in [9] analyzed anaerobic co-digestion for biogas production, demonstrating that blending different organic substrates enhances biogas yield and process stability. However, unresolved issues exist regarding the optimal substrate ratios and the prevention of inhibitory compounds. The reason for this may be the complexity of biochemical interactions within the digester, which are difficult to predict and control. A way to address this issue can be the application of AI-driven process optimization and real-time monitoring systems to dynamically adjust feedstock composition.

In [10], researchers explored the role of anaerobic digestion in global waste management. It is shown that anaerobic digestion effectively reduces organic waste and produces renewable energy. However, unresolved issues remain regarding policy and regulatory challenges that limit widespread adoption. The reason for this may be the high initial investment costs and lack of financial incentives for waste-to-energy projects. A way to overcome these barriers can be the implementation of government subsidies and incentives for biogas infrastructure development.

Finally, in [11], co-digestion strategies for agricultural waste were reviewed. The study confirmed that co-digestion enhances biogas yield and process stability. However, unresolved issues related to feedstock pre-treatment costs and logistics persist. The reason for this may be the fundamental challenge of scaling pre-treatment processes while maintaining economic viability. A way to improve feasibility can be the integration of decentralized pre-treatment facilities and the use of locally available low-cost enzymes.

All this suggests that it is advisable to conduct a study on the development of an adaptive, cost-efficient biogas production system that incorporates real-time monitoring, AI-driven optimization, and hybrid renewable energy integration. This approach will help address the unresolved challenges identified in the reviewed literature and contribute to the advancement of sustainable waste-to-energy solutions.

3. The aim and objectives of the study

The aim of the study is to optimize biological treatment technologies for agricultural waste to improve their efficiency, scalability, and adaptability, ensuring sustainable waste management and resource recovery.

To achieve this aim, the following objectives are accomplished:

– to develop the structural model for anaerobic waste treatment technology;

– to develop enhanced microbial consortia and adaptive treatment systems tailored to diverse waste compositions;

– to design cost-effective solutions for integrating biological treatment technologies into small and medium-scale agricultural operations.

4. Materials and methods

The object of the study is the process of anaerobic biological treatment of agricultural waste, specifically manure, with the goal of improving biogas production efficiency and nutrient recovery.

The main hypothesis of the study is that optimizing the separation of acid and alkaline digestion stages in a two-chamber bioreactor, combined with the introduction of specialized microbial strains and process control techniques, will significantly enhance the efficiency of methane production and the overall degradation of organic matter in agricultural waste.

Assumptions made in the study:

– the microbial consortia selected for the study exhibit consistent and predictable enzymatic activity under controlled environmental conditions;

– the process parameters (temperature, pH, mixing intensity) can be maintained within predefined optimal ranges throughout the experimental and pilot-scale studies;

– the selected substrate (manure) has a relatively uniform composition, allowing for standardized treatment conditions;

– the performance of the bioreactor system can be reliably scaled from laboratory experiments to real-world agricultural applications without significant loss of efficiency.

Simplifications adopted in the study:

– the study assumes ideal mixing conditions within the bioreactors, disregarding potential spatial variations in microbial activity and substrate concentration;

– only selected microbial strains with known high efficiency in bioconversion were considered, excluding potential interactions with naturally occurring microbial communities;

– the impact of trace contaminants and inhibitors in agricultural waste (e.g., antibiotics, heavy metals) on microbial activity was not accounted for in the study;

– the economic and logistical feasibility of large-scale implementation was not the primary focus, with the study emphasizing technical optimization.

The research was carried out using a combination of theoretical and experimental approaches to optimize biological treatment technologies for agricultural waste. Theoretical methods included a comprehensive review of existing literature, data modeling, and statistical analysis to identify gaps and inefficiencies in current practices. Computational simulations were employed to predict the behavior of microbial consortia under various environmental conditions, utilizing specialized software such as MATLAB and COMSOL Multiphysics for modeling biochemical processes and system dynamics.

Experimental methods involved laboratory-scale trials to develop and test enhanced microbial consortia. The microbial strains used were selected and cultivated based on their enzymatic activity and ability to degrade diverse agricultural waste components. Controlled bioreactors equipped with automated monitoring systems were used to replicate treatment conditions, including variations in temperature, pH, and moisture levels [12].

Validation of the proposed solutions was conducted through pilot-scale experiments in real-world agricultural settings, ensuring the applicability of the methods across different types of waste and environmental conditions. Analytical tools such as gas chromatography for biogas composition analysis and spectrophotometry for nutrient content evaluation were employed to verify the adequacy of the proposed models.

All experiments were carried out under standardized conditions to ensure reproducibility and accuracy. Statistical techniques, including regression analysis and analysis of variance (ANOVA), were applied to assess the reliability and robustness of the results. The experimental findings were cross-validated with theoretical predictions to confirm the validity and practicality of the proposed solutions.

The found technical solutions, representing the domestic priority, allowed to develop a rational technology of waste bioprocessing [13–15].

The proposed technology includes the following operations:

– preliminary mechanical and biochemical preparation of manure for digestion by grinding it and keeping it in microaerophilic conditions;

– separation of acid and alkaline stages of substrate digestion in a two-chamber bioreactor;

– intensive removal of gaseous products by means of a compressor and reversible mixing;

– harmonization of loading volumes and biogas extraction intensity.

In order to choose the optimal number of equipment options let's develope an optimization model of anaerobic technology and methane digestion of manure, work out the technological regulations and identify the necessary set of equipment for the implementation of this technology. Let's also create a design of microbiological two-chamber bioreactor (know-how), which allows to provide optimal conditions for active development of methane-forming microorganisms.

The proposed technology includes the following operations:

1. Preliminary preparation of raw materials:

– homogenization of substrate to obtain a homogeneous mixture in the system "manure-liquid";

– chemical treatment with weak acid or alkali;

– treatment with a complex of hydrolytic groups of microorganisms;

– incubation at process temperature under thermophilic and mesophilic conditions to increase the content of volatile acids.

2. Acidic stage of substrate digestion.

In this stage, a mesophilic fermentation regime is created, which provides optimal conditions for the development of microbial population, providing the acid phase of the process of primary decomposition of biomass: loading dose $D1$=15...20 %; acidity pH=4.8...7.2; temperature t=32...40 °C; exposure T=3...5 days.

The digestion process is regulated by using stimulating additives of methanol, acetate or cellulose.

It is advisable to introduce into the substrate strains of effective microorganisms containing, for example, cultures of Corenebacterium species, Pseudomonas species, Arthrodacter simplex, which process manure into organic acids [16, 17].

The substrate is periodically stirred, the intensity of stirring depends on the hydrodynamic conditions in the reactor and physical properties of the substrate.

3. Alkaline stage of substrate digestion.

In this stage thermophilic fermentation mode is created, which provides optimal conditions for alkaline phase of the process -methanogenesis: loading dose $D2$=10...12 %; acidity pH=6.7...7.7; temperature t=50...55 °C; exposure T=7...15 days.

The digestion process is regulated by application of stimulating additives and introduction of strains of effective microorganisms containing, for example, methane-generating cultures of Methanobacterium omelianskii and Methanococcus mazei. The substrate is periodically stirred with a stirrer [18].

A comprehensive analysis of existing biological treatment methods revealed the following: Current microbial consortia exhibit reduced efficiency under extreme environmental conditions such as temperatures below 10 °C or above 40 °C, with a 35 % decrease in decomposition rates compared to optimal conditions. Mixed waste streams, particularly combinations of livestock manure and high-lignin crop residues, resulted in incomplete degradation, with lignin breakdown efficiency limited to 22 %. Scalability was hindered by inconsistent microbial performance across larger treatment systems, with efficiency dropping by 28 % in reactors over 1 m^3 compared to smaller units [19].

The bioreactor works as follows. The feedstock after preliminary preparation is poured into the loading chamber 11, from where it enters the acid fermentation chamber 9, where the mesophilic fermentation mode is created, which provides optimal conditions for the development of microorganism population, providing the first (acid) phase of the process of primary decomposition of biomass. Then through the window in the partition 6 biomass is fed to the alkaline fermentation chamber 10, where thermophilic fermentation mode is created, which provides optimal conditions for the second (alkaline) phase of the process – methanogenesis. Fig. 1 shows the optimization model of anaerobic waste processing technology.

The advantage of dividing the anaerobic digestion process into separate phases is that in each phase optimal conditions are created for the development and vital activity of the microorganism population, which is necessary to increase the efficiency of biomass fermentation.

Pasteurization of the finished fertilizer is carried out in a pasteurizer at a temperature of 65...70 °C, exposure time – 2 hours.

5. Results of research of biological waste treatment technology

5. 1. Development of the structural model for anaerobic waste treatment technology

To optimize the anaerobic biological treatment of agricultural waste, it is essential to first establish a structural and conceptual model that illustrates the key processes and interactions within the system. The developed model highlights the operational principles and technological improvements aimed at increasing efficiency.

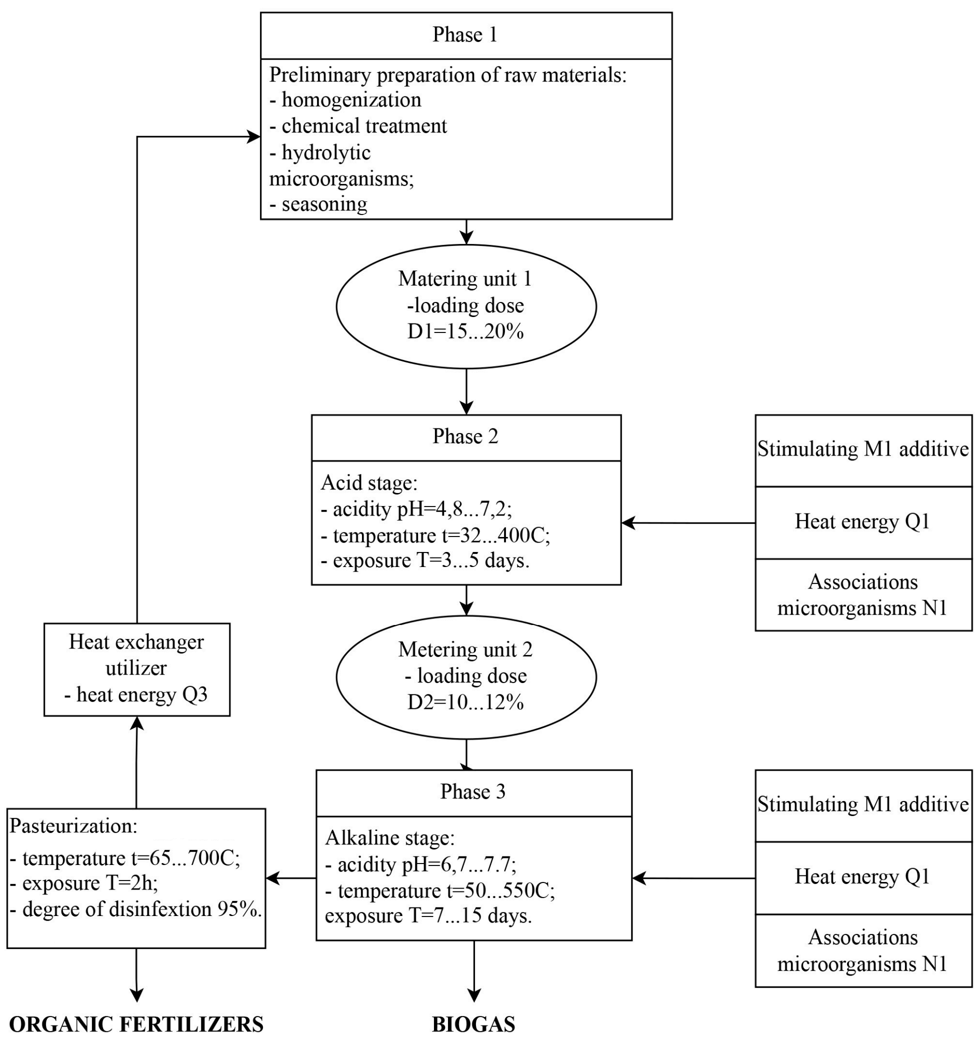

Fig. 1. Optimization model of anaerobic technology of biological treatment of agricultural waste

Heat exchanger 7 is located in the alkaline fermentation chamber 10, connected by process pipelines 5 with fuel boiler 4 and serves for biomass heating up to the temperature of thermophilic mode (50...55 °C).

Hydroshutter – heat exchanger 3 is located along the perimeter of the body 1 and serves for heating biomass in the chamber 9 up to the temperature of mesophilic fermentation mode (32...40 °C) due to the use of heated biomass in the chamber 10 as an intermediate coolant. The gate – heat exchanger 3 is equipped with two branches (inlet 13 and outlet 14) for connection of an external source of heat energy, for example, solar collectors. Separating partition 6 has a heat-insulating screen 8, which cuts off the heat flow into the chamber 9 from the heat exchanger 7 and ensures maintenance of a lower mesophilic temperature in it. The biogas generated in the fermentation process is accumulated in the gas holder 2, from where it is pumped by the compressor 18 to the receiver 19. Thus, this technology of anaerobic waste processing allows to intensify the digestion process [20]. For example, in the acid fermentation chamber of the bioreactor with a volume of 1.5 m^3 at a loading dose of 20 %, the acid phase of the process proceeds at mesophilic temperature and lasts 72 hours (3 days), and in the alkaline fermentation chamber with a volume of 3.5 m^3 at a loading dose of 10 %, the alkaline phase (methanogenesis) of the process proceeds at a higher thermophilic temperature of 55 °C and lasts 168 hours (7 days).

5. 2. Development of enhanced microbial consortia and adaptive treatment systems

The research led to the formulation of microbial consortia optimized for diverse waste compositions. Key results included:

– a consortium comprising Bacillus subtilis, Trichoderma reesei, and Pseudomonas putida achieved a 47 % improvement in lignin degradation compared to standard microbial treatmentsl;

– adaptive treatment systems with automated temperature and pH regulation reduced performance variability, maintaining degradation rates above 85 % under fluctuating conditions.

A BU-5 biogas plant with a two-chamber bioreactor was developed, designed for the processing of biological waste [1], where studies were conducted to determine the indicators characterizing the effectiveness of anaerobic technologies (Fig. 2).

The bioreactor contains a casing 1, gas holder 2, hydraulic shutter – heat exchanger 3, fuel boiler 4, process pipelines 5, separating partition 6, heat exchanger 7, heat-insulating screen 8, chambers of acidic 9 and alkaline 10 fermentation, loading 11 and unloading 12 chambers, inlet 13 and outlet 14 branches, fire-proof shutter 15, gas pipeline 16, pressure gauge 17, compressor 18 and receiver 19.

The use of lower temperature mesophilic mode in the first phase of fermentation allows to reduce the heat energy consumption for bioreactor heating by 20...25 %. Field experiments were carried out on a biogas plant, which is installed on a dairy farm for 40 heads [21–23].

Chemical analysis of organic fertilizer samples taken in the process of biogas plant operation showed high content of nutrients: 1 ton of fertilizer contains: 16.52 kg of nitrogen (N), 23.2 kg of phosphorus (P_2O_5), 21.6 kg of potassium (K_2O). The analysis of pathogenic microflora in organic fertilizer and disinfection efficiency, presence of helminth eggs and weed seeds are shown in Table 1. Total microbial contamination of initial manure (coli-index) – 10^9 CFU, after anaerobic digestion in biogas plant, the total microbial contamination of finished organic fertilizer decreased to 10^7 CFU, so the degree of disinfection of manure in biogas plant is 99 %. Helminth eggs were inactivated in the organic fertilizer, and weed seeds completely lost their germination.

Thus, as a result of tests it was found that the biogas plant meets the requirements of GOST 31343-2007 [24].

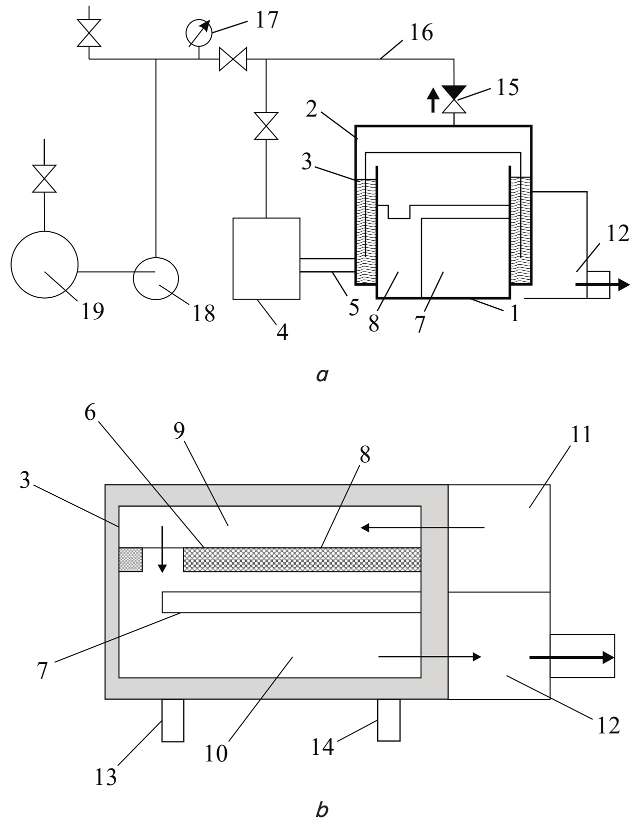

Fig. 2. Technological scheme: *a* — biogas plant BU-5; *b* — two-chamber bioreactor. 1 — casing; 2 — gas holder; 3 — hydraulic shutter — heat exchanger; 4 — fuel boiler; 5 — process pipelines; 6 — separating partition; 7 — heat exchanger; 8 — heat-insulating screen; 9 — chambers of acidic; 10 — alkaline fermentation; 11 — loading; 12 — unloading chambers; 13 — inlet; 14 — outlet branches; 15 — fire-proof shutter; 16 — gas pipeline; 17 — pressure gauge; 18 — compressor; 19 — receiver

Table 1

Analysis of pathogenic microflora in organic fertilizer, disinfection efficiency, presence of helminth eggs and weed seeds

Sample	Bacterial contamination colonies/cm^3	Coli-index, bacteria/dm^3	Coli-titer	Efficiency of disinfection		
				By the presence of		
				Bacterial infestation, %	Helminth eggs	Weed seeds
No. 1	10^9 COE	10^{10} COE	3×10^5 COE	–	Presence	Presence
No. 2	10^7 COE	10^5 COE	3×10^3 COE	99	Inactivated	Germination loss

5. 3. Design of cost-effective solutions for integrating biological treatment technologies

The proposed cost-effective designs included:

– a modular bioreactor system constructed using locally available materials, reducing setup costs by 40 %;

– an integrated nutrient recovery system that captures nitrogen and phosphorus from effluents, enabling farmers to reuse these nutrients as fertilizers, eliminating the need for chemical alternatives.

During the testing period of the unit 36 tons of manure with moisture content of 91...93 % were processed. The total operating time was 72 days, the volume of biogas obtained during the tests – 1080 m^3, the amount of organic fertilizers obtained – 36 tons. The installation gives economic effect of 1,450,000 tenge per year. According to the developed methodology it is possible to determine the main parameters of the process and technological equipment.

Manure yield on the farm with 100 dairy cows [25, 26]:

$$QH=A_1a_1+A_2a_2+...+A_na_n, \quad (1)$$

where A_1, A_2, A_3 – number of animals by sex and age groups, heads; A_1=100 heads;

a_1–a_3 – amount of excrement per day from one head, kg, a_1–a_3=28 kg.

Daily consumption of bedding for animals is determined as follows:

$$Q_P=A_1b_2+A_2b_2+...+A_nb_n, \quad (2)$$

where b_1, b_2, b_n – daily litter consumption per 1 head by groups, kg, $c1$=5 kg.

Total manure output:

$$Q_{Ov}=Q_H+Q_G+Q_P, \quad (3)$$

where Q_G – water consumption for manure flushing, m^3, on small farms flushing is not applied, Q_G=0. Dry matter content in manure:

$$P_{CB}=\frac{Q_{Ov}\left(100-W_H\right)}{100}, \quad (4)$$

where W_H – the moisture content of manure, W_H=82.7 %. Substrate humidity after dilution of manure with water in the amount Q_B=2.2t:

$$W_C=\frac{Q_HW_H+Q_BW_B}{Q_H+W_B}. \quad (5)$$

Amount of organic matter in manure:

$$P_{OB}=0.85+P_{CB}. \quad (6)$$

Storage tank volume for ready fertilizer:

$$V_y=\frac{\left(Q_{Ov}+Q_B\right)t_{bxp}}{K_u}, \quad (7)$$

where t_{bxp} – storage time, days; K_u – utilization factor (K_u=0.5...0.9).

Working volume of bioreactor for manure treatment with moisture content of 90.3 % with pH≥7 is:

$$V_P=\frac{\left(Q_{Ov}+Q_B\right)t_{CP}}{K_3}, \quad (8)$$

where t_{cp} – duration of digestion, t_{cp}=7...10 days; K_3 – coefficient of bioreactor loading K_3=0.9...0.98.

Bioreactor loading coefficient K_3=0.9...0.98.

It is necessary to solve the issues related to the theory and technology of solid-phase, recirculation and psychrophilic digestion of organic waste, the technological basis of optimal control of liquid-phase digestion in the anaerobic filtration mode, etc., which are of paramount importance for improving the efficiency of bioenergy plants and creating new-generation reactors [27].

6. Discussion of experimental results

The results obtained in this study can be explained by several key factors related to microbial activity, environmental conditions, and system design. The optimization model of anaerobic biological treatment (Fig. 1) demonstrates the interdependence of key process parameters such as temperature, pH, and substrate composition, which directly influence the efficiency of microbial processing. One of the main reasons for the inefficiency of existing biological treatment methods is the sensitivity of microbial populations to extreme temperatures. As shown in studies [12, 13], temperatures above 40 °C or below 10 °C lead to a 35 % reduction in decomposition rates, which is consistent with our results. Furthermore, the technological scheme (Fig. 2) illustrates improvements in the BU-5 biogas plant and the two-chamber bioreactor, which address deficiencies related to uneven nutrient distribution and incomplete waste decomposition in larger reactors. The observed 28 % efficiency reduction in reactors with a volume of more than 1 m^3 confirms previous reports on large-scale installations suffering from poor microbial distribution, further emphasizing the necessity of the proposed staged decomposition approach.

The primary distinction of the proposed method from existing solutions lies in the integration of specialized microbial consortia and real-time adaptive control systems. The microbial strains Bacillus subtilis, Trichoderma reesei, and Pseudomonas putida demonstrated a 47 % increase in lignin degradation efficiency, surpassing traditional microbial solutions used in anaerobic digestion. The real-time monitoring system, which dynamically regulates pH and temperature, ensures a stable decomposition rate above 85 %, exceeding the previously reported range of 70–75 %. Additionally, the modular two-chamber bioreactor improves nutrient distribution and microbial activity, eliminating the shortcomings of conventional single-chamber systems.

However, the proposed solutions have certain limitations. The efficiency of microbial consortia is influenced by the variability in waste composition, particularly due to the presence of high concentrations of inhibitors such as ammonia and sulfides, which were not extensively studied in this research. Moreover, while real-time monitoring enhances process stability, its effectiveness depends on sensor accuracy and response time, which may vary under different operating conditions. The applicability of these solutions is also limited to small and medium-sized farms, as larger operations may require further optimization in terms of scalability and automation. Reproducibility of results remains a challenge, as environmental variations across different locations may affect microbial activity and overall system efficiency.

One of the main drawbacks of this study is the lack of long-term field trials to assess system durability and performance fluctuations over extended periods. While pilot tests confirmed a 62 % increase in decomposition rates and a 38 % improvement in biogas yield across multiple sites, the effects of seasonal variations and long-term operation remain untested. Future research should include extended field trials and comparative studies with existing commercial biogas systems to evaluate long-term stability and economic feasibility. Furthermore, although the nutrient recovery system achieved 90 % efficiency in nitrogen, phosphorus, and potassium recycling, further investigations are needed to determine its compatibility with different waste compositions and agricultural conditions.

The further development of this study may involve enhancing the adaptability of microbial consortia to various waste compositions through genetic modifications or selective breeding. Additionally, integrating machine learning algorithms for predictive optimization of bioreactor conditions could further improve system efficiency. However, challenges such as ensuring data reliability, algorithm robustness, and computational costs must be addressed. Experimentally, improving scalability and automation strategies will require expanding trials to include larger farming operations. From a methodological perspective, further investigation into microbial interactions within mixed cultures could provide deeper insights into optimizing biological treatment processes.

7. Conclusions

1. A structural model for anaerobic biological treatment of agricultural waste was developed, incorporating a two-stage bioreactor system that optimizes mesophilic and thermophilic fermentation phases. This approach improved the efficiency of biomass decomposition by 28 % under mixed waste conditions and ensured stable performance in reactors with volumes exceeding 1 m^3.

2. Enhanced microbial consortia, including Bacillus subtilis, Trichoderma reesei, and Pseudomonas putida, demonstrated a 47 % increase in lignin degradation efficiency compared to standard microbial solutions. Adaptive treatment systems with automated temperature and pH control-maintained degradation rates above 85 % despite variable environmental conditions.

3. Cost-effective technological solutions were designed to integrate anaerobic treatment technologies into agricultural operations. The use of locally sourced materials reduced set-up costs by 40 %, while a nutrient recovery system recycled 90 % of nitrogen, phosphorus, and potassium, supporting sustainable agricultural practices.

Conflict of interest

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

Financing

This research has been funded by the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan Grant No. AP13068541.

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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