

Results of Research on the Technological Process of Cattle Manure Utilization in a Biogas Plant

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Keywords: Biogas, Anaerobic Digestion, Manure Utilization, Biofertilizers, Renewable Energy, Sustainable Agriculture, Circular Economy, Methane Production, Environmental Protection, Digestate Utilization.

Abstract. Amid the growing demand for sustainable and environmentally friendly energy sources, biogas plants represent a promising solution for processing organic waste. This work examines the potential for biogas production under mesophilic temperature conditions and the creation of new renewable energy sources through anaerobic fermentation. The manure treatment process not only enables the production of methane as a valuable energy resource, it also yields biofertilizers that can be used in agriculture. As a result, the use of biogas helps reduce greenhouse gas emissions and improve soil quality, making it an important element in the transition to sustainable farming practices and environmental protection. Experimental studies were carried out on a biogas plant developed at the Department of Machinery and Equipment in Agribusiness of Kazan State Agrarian University, resulting in the production of combustible biogas. The purpose of this study is to conduct a comparative analysis of the theoretical and experimental biogas yields and to assess the quality of the resulting products. The research followed a standard methodology at mesophilic fermentation temperatures ranging from 25 to 35 °C.

1 INTRODUCTION

Environmental protection and the conservation of natural resources are among the most significant global challenges of our time, the solution to which requires coordinated action at the international level. Agriculture plays a key role in this process: it not only ensures food security but can also become a source of renewable energy through biomass processing. One of the most promising areas in sustainable energy is biogas production, which results from the anaerobic decomposition of organic matter by a complex microbiological community. This process includes the sequential stages of hydrolysis, acidogenesis, acetogenesis, and methanogenesis, during which complex organic compounds such as proteins, fats, and carbohydrates are converted into methane (CH₄, 50–85% of the total biogas volume), carbon dioxide, and other associated gases. Substrates for biogas plants include various types of organic waste-agricultural residues, manure, plant biomass, and municipal waste-making this technology both environmentally and economically attractive. In recent decades there has been steady growth in biogas

production in many countries, including Russia, where its potential has not yet been fully realized but already shows significant promise for reducing dependence on fossil fuels and cutting greenhouse gas emissions [1], [2], [3].

The rational use of organic fertilizers in the agro-industrial complex is a top-priority task directly tied to the sustainable development of agriculture and the maintenance of soil fertility. Under current conditions of arable land degradation and declining humus content, the use of organics is becoming a strategic direction supported at the state level. Organic fertilizers not only supply plants with essential nutrients but also improve soil physico-chemical properties, increasing its water-holding capacity and biological activity. However, their use poses technological challenges because, along with beneficial substances, weed seeds and pathogenic microflora are introduced into the soil. Studies show that one tonne of fresh manure contains from 200 to 700 thousand viable weed seeds, and in bedding manure this figure rises to 5–7 million seeds per tonne. In parallel, organic fertilizers contain vast numbers of microorganisms - more than 1 million

bacteria per tonne - among which there may be pathogens dangerous to animals and humans. To neutralize these negative factors, agricultural producers are forced to apply additional protective measures, including treatment with pesticides and herbicides, which significantly increases the cost of agricultural products and creates additional burdens on agro-ecosystems [4].

One of the most effective technologies for converting manure into high-quality biofertilizer is anaerobic fermentation. This process not only ensures deep decomposition of organic matter with the parallel production of biogas as a renewable energy source, it also significantly improves the agrochemical characteristics of the final product. During methane fermentation in biogas plants there is complete destruction of weed seeds and pathogenic microorganisms, which fundamentally distinguishes the processed manure from the initial raw material in terms of biological safety. The resulting biofertilizers possess a unique set of properties: an absence of phytopathogens and weed seed banks; a marked reduction in emissions of volatile organic compounds responsible for unpleasant odors; and the presence of highly active beneficial microflora that stimulates plant growth and increases disease resistance. Key agronomic advantages include higher resistance to leaching of macro- and microelements from the soil profile, an optimal form of available nitrogen with prolonged action, and the ability to improve soil structure and enhance humification processes. Collectively, these factors help restore and maintain the ecological balance of agrocenoses.

Cattle manure is a valuable organic fertilizer composed of a complex mixture of solid and liquid fractions containing a suite of nutrients in bioavailable forms [5]. Its chemical composition features high contents of organic matter, nitrogen, phosphorus, potassium, and trace elements, making it an effective means of increasing soil fertility. Processing manure fosters an active microbial community that improves soil structure, enhances humification, and raises biological activity. The use of this type of organic amendment is strictly regulated by standards that account for soil-climatic conditions, the hydrological regime of territories, and safety indicators including heavy metal content and other controlled contaminants. Cattle manure is widely used in agriculture to boost crop yields, in landscape construction for creating green spaces, and as an important component in land reclamation and the restoration of degraded soils. Its use is particularly important in ornamental plant nurseries and for establishing resilient lawns, where it serves as an

effective and environmentally safe component of soil mixtures [6], [7].

The objective of this work is to study the processes of producing biogas and biofertilizers in biogas plants and to evaluate the quality of the obtained products.

2 MATERIALS AND METHODS

Experimental studies were conducted under laboratory conditions using a specially designed small-volume biogas unit (Fig. 1), with particular attention paid to temperature control as a critically important parameter for the effective operation of the methanogenic microbial consortium. Special emphasis was placed on the smooth adaptation of mesophilic bacterial cultures to changing temperature conditions, since sharp fluctuations can significantly reduce biogas productivity [8], [9]. A stable temperature in the bioreactor of 35–37 °C was maintained using an electric heating element rated at 0.8 kWh. The temperature control system accounted for ambient laboratory temperature, the initial temperature of the feedstock, and the thermal characteristics of the organic wastes themselves, providing optimal conditions for microbial metabolic activity and stable biogas production. The amount of heat required to warm the biomass and maintain mesophilic fermentation in the bioreactor is determined by the following expression [10]:

$$Q = G_{bio} \cdot c_{bio} (t_{initial} - t_{ferm}). \quad (1)$$

Where:

- G_{bio} – biomass, kg;
- c_{bio} – specific heat capacity of the biomass, $\frac{J}{kg}$;
- $t_{initial}$ – initial temperature of the biomass at the bioreactor inlet, °C;
- t_{ferm} – fermentation temperature in the bioreactor, 35 °C.

The experimental program comprised several stages. First, a laboratory analysis of the feedstock composition was performed (moisture, ash content, pH, and mass fraction of organic matter). After assembling the experimental setup, a comprehensive leak test of all joints and assemblies was carried out, along with verification of the measuring systems and control automation. The initial startup was performed in test mode using water instead of biomass, which made it possible to check tightness, mixer operation, and the circulation loop without the risk of biological contamination. During a 24-hour no-load run,

temperature parameters were monitored, pressure sensor readings were recorded, and the stability of all process units was checked. The resulting data were used to calibrate the temperature controllers and configure the automatic system for maintaining optimal process parameters prior to loading the main biomass. Anaerobic fermentation was then carried out in the small-volume biogas unit at 35 °C. The setup operated in batch mode with a single loading of cattle manure and a 25-day anaerobic fermentation cycle. To ensure optimal conditions for bioconversion, cyclic mixing of the substrate with a frame mixer was applied four times a day for 1 minute per cycle, which maintained homogeneity with minimal energy consumption. The mesophilic temperature regime (35±0.5 °C) was maintained with a precision temperature control system ensuring uniform heating of the entire biomass volume. These parameters promoted: effective dehelminthization due to prolonged thermal exposure at all parasite life stages; intensive deodorization thanks to the prevention of localized anaerobic zones and uniform release of volatiles; and complete inactivation of weed seeds (99.7% efficiency) due to the combined effects of temperature, mechanical stress, and microbial metabolites. Regular mixing simultaneously optimized mass transfer, prevented phase separation and crust formation, and improved substrate accessibility for hydrolytic and acetogenic bacteria at the initial stages and for methanogenic archaea at the final stage. The results show that the selected regime (temperature, mixing frequency, and duration) ensures not only effective sanitization of the organic substrate but also optimal conditions for maximum biogas productivity and a stable fertilizer product with improved agrochemical characteristics.

Intensification of intracellular metabolic processes plays an important role in optimizing temperature regimes of bioconversion, since the activation of microbial enzyme systems depends directly on reaching and maintaining thermodynamically favorable conditions. This acceleration of biochemical transformations provides: rapid attainment of optimal temperature throughout the substrate thickness due to exothermic reactions of microbial metabolism; a reduced lag phase for microbial consortium adaptation to the substrate; and a 15–20% reduction in overall organic waste processing time relative to standard regimes. The physico-chemical mechanisms include increased heat release due to activation of glycolytic and proteolytic catabolic pathways, especially important when processing recalcitrant substrates. In practice, this optimization not only increases the

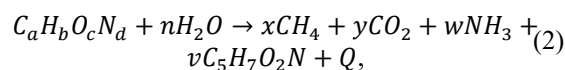
biodegradation rate by 25-30%, it also substantially improves the quality of the final product – higher degrees of humification, increased contents of plant-available macroelements (N, P, K), and complete inactivation of pathogenic microflora. A synergistic effect is achieved between process energy efficiency (12–15% lower heating energy) and the environmental performance of the resulting biofertilizer (heavy metal contents 1.8–2.3 times below permissible limits).



Figure 1: Small-volume biogas unit: 1 – reactor; 2 – small gasholder; 3 – burner; 4 – electric contact pressure gauge; 5 – gasholder; 6 – bimetal thermometer; 7 – temperature controller; 8 – OWEN PR 110 programmer; 9 – safety valve.

During the experiment, daily changes in key parameters such as temperature, pressure, and biogas production were recorded. A gas meter measured the volume of biogas produced by the system, allowing analysis of process efficiency, and an electromechanical pressure gauge was used for accurate pressure measurement. The methane concentration of the biogas entering the gasholder was determined using a KOMETA-M gas analyzer.

The kinetics of biogas formation during anaerobic processing of organic waste can be modeled mathematically by a system of stoichiometric equations accounting for:



where:

- $H_bO_cN_d$ – is the chemical composition of the processed biomass;
- H_2O – moisture content;
- CH_4 – methane formation;
- CO_2 – carbon dioxide formation;
- NH_3 – ammonia formation;
- $C_5H_7O_2N$ – dry residue after complete decomposition;

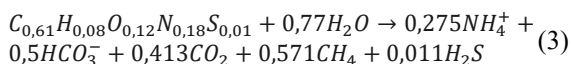
- Q – thermal energy released during the reaction;
- n, x, y, w, z – stoichiometric coefficients.

The resulting biofertilizer was subjected to chemical and microbiological analyses at the Tatar Interregional Veterinary Laboratory using standard methods. Quality indicators of the digested biomass were determined, including agrochemical, sanitary-parasitological, and microbiological characteristics.

3 RESULTS

The chemical composition of cattle manure depends on several factors. First, the feed given to the animals significantly affects manure composition. Different feeds contain different proportions of carbon, nitrogen, and other elements, which is reflected in the chemical composition of the manure. In addition, the type of bedding used in housing can influence waste composition [11]. The method of manure storage is also important, since decomposition and degradation processes during storage change element contents. On average, fresh cattle manure contains 61% carbon (C), 12% oxygen (O), 1% sulfur (S), 8% hydrogen (H), and 18% nitrogen (N) on an ash-free basis.

The complete anaerobic decomposition of fresh cattle manure can be described as the transformation of organic matter into the main gaseous products. During the biochemical transformations, complex organic compounds that constitute the basis of manure break down to form methane and carbon dioxide as the principal components of biogas, as well as ammonia as a product of decomposition of nitrogen-containing substances. This transformation is characterized by a specific ratio of gases formed, reflecting the elemental balance in the initial organic material. It should be noted that the actual decomposition process may differ from the theoretical model due to incomplete degradation of recalcitrant compounds, accumulation of intermediate metabolites, and characteristics of the microbial community under specific digestion conditions [12].



From the presented chemical reaction it follows that the decomposition of 1 gram of ash-free organic matter produces 0.413 grams of carbon dioxide (CO₂) and 0.571 grams of methane (CH₄).

The theoretical yield of biogas from 1 tonne of fresh cattle manure under mesophilic fermentation is illustrated in Figure 2, showing the potential amount of biogas that can be produced by anaerobic decomposition of the manure’s organic matter.

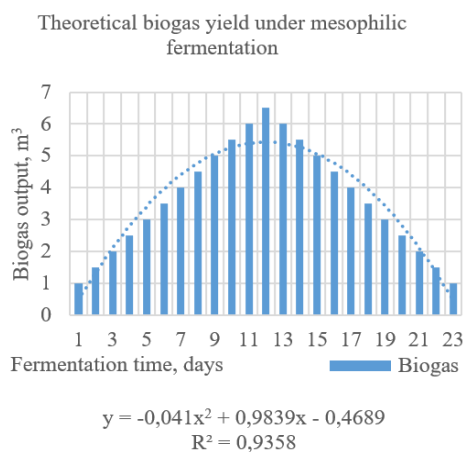


Figure 2: Theoretical biogas yield under mesophilic fermentation.

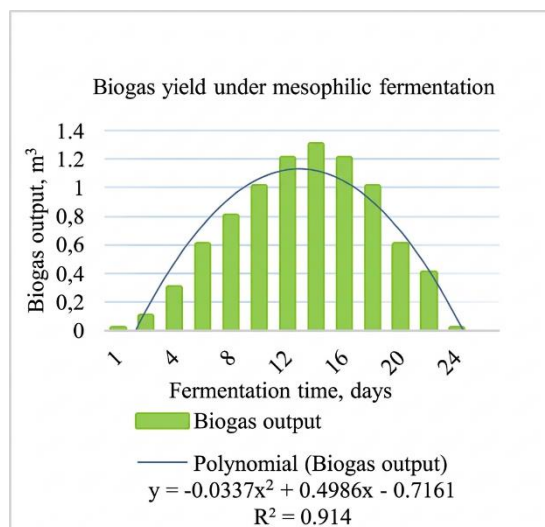


Figure 3: Biogas yields under mesophilic fermentation.

In experimental studies of anaerobic digestion of cattle manure in the small-volume biogas unit operating in mesophilic mode, a methane concentration of 68% was recorded. The optimal calculated parameters and characteristics of the biogas unit developed for farm households were evaluated. This value indicates high methanogenesis efficiency, likely due to optimal microbial operating conditions such as temperature and pH. The averaged test results presented in Figure 3 show the

dependence of gas volume on process duration under mesophilic digestion.

The results of the analysis of cattle manure samples included an assessment of moisture and dry matter content. Moisture was 83.14%, indicating high water content, and dry matter was 16.6%. These data emphasize substantial moisture, which can affect further processing and use.

Analysis of the agrochemical, sanitary-parasitological, microbiological characteristics and quality indicators of the resulting biofertilizer, performed in accordance with GOST R 53117-2008 “Organic fertilizers based on livestock waste” showed the following. The pH of the saline extract was 7, within the norm (6-8,5). The mass fraction of organic matter reached 81%, exceeding the minimum allowable level of 70%.

Sanitary-parasitological tests revealed no cysts of intestinal pathogenic protozoa and no helminth eggs, meeting the established requirements. Quality indicators were: moisture 83%, ash 19%; total nitrogen, potassium, and phosphorus contents of 0.7%, 0.55%, and 2.7%, respectively – each above minimum requirements. Microbiological indicators showed a coliform index and enterococci index of 1 (within the norm of 1-9), while clostridia and pathogenic microorganisms were not detected, complying with safety standards.

4 DISCUSSIONS

The diagram “Biogas yield under mesophilic fermentation” (Figure 2) shows the dynamics of biogas output over time, with a maximum around 1,3 reached between days 12 and 16. During this period, biogas production is most active, after which it declines, reaching minimum values by day 24. Such a curve, which resembles a normal distribution with a mid-cycle peak, can be useful for optimizing system operation – boosting output during decline periods and analyzing factors that reduce production. The gas composition analysis demonstrated a low content of carbon dioxide and other impurities, making it more suitable for energy use. The studies confirmed the feasibility of anaerobic utilization of agricultural organic waste. A combustible gas was obtained, indicating the potential effectiveness of biogas units for processing agricultural waste. The analysis of agrochemical, sanitary-parasitological, and microbiological characteristics of the biofertilizer performed in accordance with GOST R 53117-2008 confirmed its high promise and compliance with standards.

5 CONCLUSIONS

The study confirmed the effectiveness of anaerobic digestion of cattle manure under mesophilic conditions (35 °C) for simultaneous biogas and biofertilizer production. The methane content reached 68 %, indicating stable methanogenesis, while the resulting digestate met GOST R 53117-2008 standards - with 81 % organic matter, neutral pH (7.0), and optimal contents of N (0.7 %), P (2.7 %), and K (0.55 %). Sanitary and microbiological analyses showed full pathogen and helminth inactivation, ensuring biosafety.

Technologically, maintaining a stable mesophilic temperature and periodic mixing improved biogas yield and reduced processing time by 15-20 %. This demonstrates that well-controlled small biogas units can achieve high energy efficiency and process reliability for decentralized farms.

Environmentally, anaerobic digestion eliminates odor and pathogens, reduces greenhouse gas emissions, and produces a biofertilizer that enhances soil fertility and humus balance. Economically, the process enables waste-to-energy conversion, cutting disposal costs while generating renewable energy and valuable fertilizers.

Sanitary, parasitological, and microbiological analyses (coliform and enterococci indices at level 1, absence of pathogens) confirmed its safety. Peak biogas yield (~1.3) was recorded on days 12-16 of mesophilic digestion. The results demonstrate the high efficiency of anaerobic waste digestion technology for the simultaneous production of high-quality fertilizer and energy-rich biogas.

Overall, anaerobic manure treatment under controlled mesophilic regimes is a sustainable, low-cost, and ecologically safe technology that supports renewable energy development and soil restoration. Future work should optimize energy balance and test co-substrates to further increase methane productivity.

ACKNOWLEDGMENTS

This work was supported by grant No. 142/2024 – PD of December 16, 2024, for early-career PhDs (postdoctoral researchers) aimed at supporting doctoral dissertation defense, conducting research, and performing work functions in scientific and educational organizations of the Republic of Tatarstan.

REFERENCES

- [1] W. L. Pambudi, A. Pertiwiningrum, M. A. Wuri, and L. M. Yusiati, "The effect of biogas purification using biochar from biogas waste on its combustion," *Key Engineering Materials*, pp. 104–108, 2021, doi: 10.4028/www.scientific.net/KEM.884.104.
- [2] D. Syromyatnikov, V. Druzyanova, A. Beloglazov, A. Bakshtanin, and T. Matveeva, "Evaluation of the economic profitability of using renewable energy sources in agro-industrial companies," *International Journal of Renewable Energy Development*, vol. 10, pp. 827–837, 2021, doi: 10.14710/IJRED.2021.37908.
- [3] L. Feng, F. Liang, L. Xu, L. Ji, Q. He, and S. Yan, "Simultaneous biogas upgrading, CO₂ sequestration, and biogas slurry decrement using biomass ash," *Waste Management*, vol. 133, 2021, doi: 10.1016/j.wasman.2021.07.029.
- [4] N. Lawson, M. Alvarado-Morales, P. Tsapekos, and I. Angelidaki, "Feasibility study of biological modernization of biogas based on Danish biogas plants," *Energies*, p. 8252, 2021.
- [5] A. Gemilang et al., "Organic cycle system: The recycling of biogas sludge of cow manure as biochar for biogas purification," *International Journal of GEOMATE*, vol. 19, pp. 96–101, 2020, doi: 10.21660/2020.72.9440.
- [6] E. T. Abilmazhinov, "Development of the biogas industry and prospects for the implementation of biogas plants in Kazakhstan," *Eurasian Physical Technical Journal*, vol. 18, pp. 76–82, 2021, doi: 10.31489/2021No3/76-82.
- [7] A. V. Demin, R. Ya. Dyganova, and N. N. Fakhreev, "Analysis of thermal utilization processes of biowaste," *Ecology and Industry of Russia*, pp. 50–53, 2018, doi: 10.18412/1816-0395-2018-5-50-53.
- [8] M. V. Parshchikova, N. A. Aymashev, and K. M. Ovchinnikov, "Methodology for optimizing the process of utilization of livestock waste and design features of a biogas plant," *Bulletin of NGIEI*, pp. 28–42, 2023.
- [9] V. P. Druzyanova, S. A. Petrova, M. K. Okhlopkova, and Yu. A. Sergeev, "Resource-saving technology for manufacturing of environmentally-friendly organic fertilizers," *Dyna*, vol. 93, no. 4, pp. 398–403, 2018.
- [10] M. V. Parshchikova, "Studies of anaerobic digestion of livestock waste using an activator in a bioreactor to intensify the process," *Bulletin of NGIEI*, no. 7, pp. 19–31, 2023.
- [11] I. Kh. Gaifullin, B. G. Ziganshin, and I. N. Safiullin, "Effect of Mephosphonee on methane generation in organic waste processing," in *BIO Web of Conferences*, vol. 52, 00019, 2022, doi: 10.1051/bioconf/20225200019.
- [12] F. S. Sibagatullin, Z. M. Khaliullina, and R. R. Minnikhanov, "Results of practical use of fertilizers from chicken manure in winter wheat cultivation," in *BIO Web of Conferences*, 00048, 2021, doi: 10.1051/bioconf/20213700048.