



Received: 27/02/2026

Revised: 15/08/2026

Accepted: 28/09/2026

Published online: 30/09/2026

Original Research Article



Open Access under the CC BY -NC-ND 4.0 license

UDC 53.097; 539.893

DEVELOPMENT OF A BIOREACTOR HEATING SYSTEM USING A GROUND-SOURCE HEAT PUMP

Sakipova S.E., Smagulov Zh.K.*, Bekturganov Zh.S., Ismailov Zh.T.,
Kartbayeva G.T., Duisenbayeva M.S., Ospanova D.A.

Buketov Karaganda National Research University, Karaganda, Kazakhstan

*Corresponding author: smagul@mail.ru

Abstract: The article presents an evaluation of the performance of a ground-source heat pump system designed to maintain a specific temperature regime within a biogas bioreactor. The novelty and distinctive feature of the installation lie in its use of renewable thermal energy sources. For the first time, a system with an external ground-source heat pump circuit consisting of four boreholes with copper U-shaped tubes through which the coolant circulates has been developed. The system's design, operating principle, and technical specifications are described. An assessment of the thermal energy output, accounting for the efficiency characteristic of the external circuit of a ground-source heat pump is shown.

Keywords: bioreactor, borehole, ground-source heat pump, heat pump, thermal efficiency.

1. Introduction

In the context of global climate change and depletion of natural resources, the transition to sustainable energy sources such as biogas is becoming a necessary condition for ensuring energy security and environmental sustainability. Indeed, a significant portion of industrial and household organic waste can serve as feedstock for the production of biogas and biomethane, paving the way for one of the most promising and vital trends in the evolution of the modern energy sector [1-9].

Biomethane and biogas, produced through the anaerobic digestion of organic waste (manure, sewage sludge, food waste, agro-industrial by-products, biological residues, etc.), possess significant energy value, as they can be used as fuel or for the generation of electricity and heat. The environmentally safe processing of agricultural waste to produce biogas makes it possible to minimize carbon emissions, reduce dependence on fossil fuels, and cut operating costs [10]. Producing biogas from waste as an effective solution for mitigating negative environmental impacts represents a significant step toward adopting renewable energy sources and establishing a sustainable global energy system [2, 7]. Along with agricultural waste, kitchen waste from catering establishments also serves as a promising substrate for decentralized biogas production, facilitating the implementation of circular economy principles and providing a cost-effective solution to energy supply and waste management issues on university campuses [6]. It is essential to adopt advanced anaerobic digestion technologies that optimize traditional digestion systems at wastewater treatment plants and waste processing facilities. These innovations—such as thermal hydrolysis and staged digestion—encompass pretreatment methods and system modifications that boost biogas yields and enhance bio-waste processing. Hundreds of biomethane production facilities have been established and are successfully operating in many countries,

integrating it into their national energy systems using advanced digestion technologies to achieve energy neutrality – or even positive energy. A solar ground-source heat pump system featuring a vertical borehole heat exchanger was developed and experimentally tested under the climatic conditions of Almaty and Astana [10, 11]. Modern 3D numerical models of heat and mass transfer and fluid dynamics were created and verified using experimental data, enabling a detailed analysis of the system's performance. Experimental studies demonstrated that the system achieves a coefficient of performance in the range of 2.11–2.76, confirming its energy efficiency.

Due to its vast land resources and favorable climatic conditions, Kazakhstan possesses significant potential for the development of agriculture and livestock farming. Biomass generated during grain harvesting—specifically large volumes of straw—can be viewed as a potential substrate for biogas production. Livestock waste complements these plant-based residues. As the global community strives for a cleaner and more sustainable energy future, the development of sustainable energy innovations must help address global challenges related to the energy transition and the achievement of carbon neutrality. From a practical standpoint, the primary objectives for most farms acquiring a biogas plant are energy savings and waste management. Depending on the characteristics of the biomass being processed, different operating modes are employed to ensure effective anaerobic digestion: mesophilic (temperature range of 35–38°C) or thermophilic (50–55°C) [4, 5]. The biogas production process relies on the anaerobic digestion of organic matter within a sealed vessel (bioreactor) in the absence of oxygen; microorganisms break down the organic material, releasing methane and carbon dioxide [8, 10–13]. The efficiency of the biogas production process depends directly on maintaining a stable temperature within the bioreactor. Clearly, the climatic conditions of Central Kazakhstan necessitate continuous heating of the bioreactor.

Practice shows that the efficiency of the biomass fermentation process and biogas production directly depends on the temperature regime inside the reactor [5, 8, 14]. There are indicated the need to maintain a biomass heating regime within the bioreactor that ensures the efficient extraction of valuable components. For mesophilic processes, the optimal fermentation temperature should be maintained in the 42–48°C range, requiring the bioreactor's thermal regime to be consistently upheld regardless of seasonal ambient temperature fluctuations throughout the year. The biomass inside the bioreactor chamber must be mixed regularly [12].

As shown in an effective solution for maintaining the thermal regime of a bioreactor is the use of a so-called “water jacket” (thermal jacket), consisting of parallel pipes placed inside the lower part of the bioreactor body together with a special bubbling device. A heated fluid circulates through the jacket's pipes within the vessel, maintaining the temperature within the range required for active biomass fermentation. [15] presents experimental results in which the water jacket was heated by burning coal-water slurry in a specially designed unit featuring a radially rotating nozzle. However, despite the efficiency gains achieved by enriching coal-water fuel through electrohydraulic processing, its use as a heat source for biomass remains relatively costly in terms of practical implementation.

Therefore, it is proposed to use more accessible renewable thermal energy sources—specifically, a ground-source heat pump combined with a solar panel system. The GSHP utilizes heat from the ground and is supplemented, as needed, by electrical units powered by the solar panels.

The proposed overall concept for the bioreactor heating system comprises three main components:

- 1) A ground-source heat pump (GSHP) that extracts heat from deep soil layers;
- 2) An electricity generation system using solar photovoltaic panels;
- 3) A controlled heating system designed to distribute thermal energy throughout the bioreactor volume to ensure uniform heating of the biomass.

At this stage, the implementation of a ground-source heat pump is being considered, along with the determination of the thermal capacity required to maintain the bioreactor's thermal regime, taking into account the specified volume of biomass to be processed.

2. Methodology of experimental research

The object of the study is the thermal control system for a cylindrical bioreactor designed to produce biogas through the processing of organic agricultural waste. The design layout and operating principle of the bioreactor are described in detail in [16]. The technical result of the solution is improved energy efficiency through connection to renewable energy sources; enhanced quality of biogas and fertilizers due to uniform mixing and temperature control; and reduced operating costs combined with a simplified design. The stated technical result is achieved by a proposed bioreactor for processing organic waste, comprising a cylindrical

body, pipes for loading, unloading, and draining, a sparging channel, heating elements, a pressure gauge, a thermometer, and a mechanical stirrer connected to a reduction gear.

The heating elements are positioned in the lower part of the bioreactor along its perimeter, the sparging channel is also located in the lower part of the body, and the bioreactor's power supply system is connected to a renewable electricity source.

2.1 Design and operating principle of a ground source heat pump

The ground-source heat pump system comprises three circuits: an external circuit located in the ground that collects thermal energy; a second circuit consisting of the heat pump itself, where the heat-transfer fluid enters the evaporator and its temperature is raised to the required level; and a third circuit that directly serves the bioreactor heating system. Let us consider the external circuit of the bioreactor's thermal control system, which utilizes a ground-source heat pump (GSHP). The GSHP operates on a principle inverse to that of a standard refrigerator: it extracts low-grade heat from the environment (soil, water, or air), raises its temperature, and transfers it to the heating system. In this instance, the GSHP utilizes heat from the ground at a depth where the temperature is far more stable than at the surface. At depths of approximately 20 meters or more, the soil does not freeze, even when surface temperatures drop to between -35°C and -40°C . The Earth's subsurface layer acts as a thermal reservoir with virtually unlimited capacity. This phenomenon is successfully employed in numerous technologies for both residential heating and the support of various industrial processes.

The GSHP operates by transferring low-temperature heat from the deep soil (a stable heat source) to the end-user via a closed-loop system utilizing a refrigerant and a compressor [16]. The pump extracts low-grade heat from the ground through a heat-transfer fluid circuit (using antifreeze), evaporates the refrigerant, compresses it to raise its temperature, and transfers the heat to the heating system; the cooled refrigerant then returns to the evaporator. To implement the GSHP, preparatory work was carried out at the experimental site, resulting in the drilling of four boreholes, each 21 meters deep and spaced 5 meters apart (Fig. 1).



Fig.1. Ground-source heat pump experimental site:
a) general view of borehole drilling; b) blue markers indicate boreholes along the trench.

U-shaped copper pipes with a diameter of 32 mm are installed in the drilled boreholes; each is encased in an outer plastic casing pipe with a diameter of 150 mm (Fig. 2). The U-shaped copper pipes are completely filled with heat-transfer fluid, leaving no voids. At the top, the vertically installed U-shaped pipes are connected in series. In the lower section of the borehole, the space between the vertical pipes inside the plastic casing is filled with groundwater from a depth of 4 m to 20 m below the surface — meaning the so-called groundwater zone spans 16 m. The outer pipe is hermetically sealed at the top. The upper space inside the plastic casing between the copper pipes is filled with air; thus, the air zone extends from 0 to 4 m below the surface.

A powerful pump circulates the heat transfer fluid (an ethylene glycol solution/antifreeze) under pressure through all four boreholes: it flows first into the outermost copper U-shaped pipe of the first borehole, then passes under pressure from the top into the adjacent second borehole, and so on. Upon exiting the fourth borehole, the heated fluid passes through a heat exchanger assisted by a compressor into a secondary circuit, where it transfers heat to a "water jacket" system to warm the organic mass within the bioreactor. The spent, cooled fluid is then pumped back into the geothermal boreholes. No additional cooling equipment is required to return the fluid to the primary geothermal circuit in the ground and prepare it to absorb heat again; this occurs naturally due to the physics of the refrigeration cycle and the inherent properties of the soil. Thus, the heat transfer fluid continuously circulates counter-clockwise through the geothermal piping.

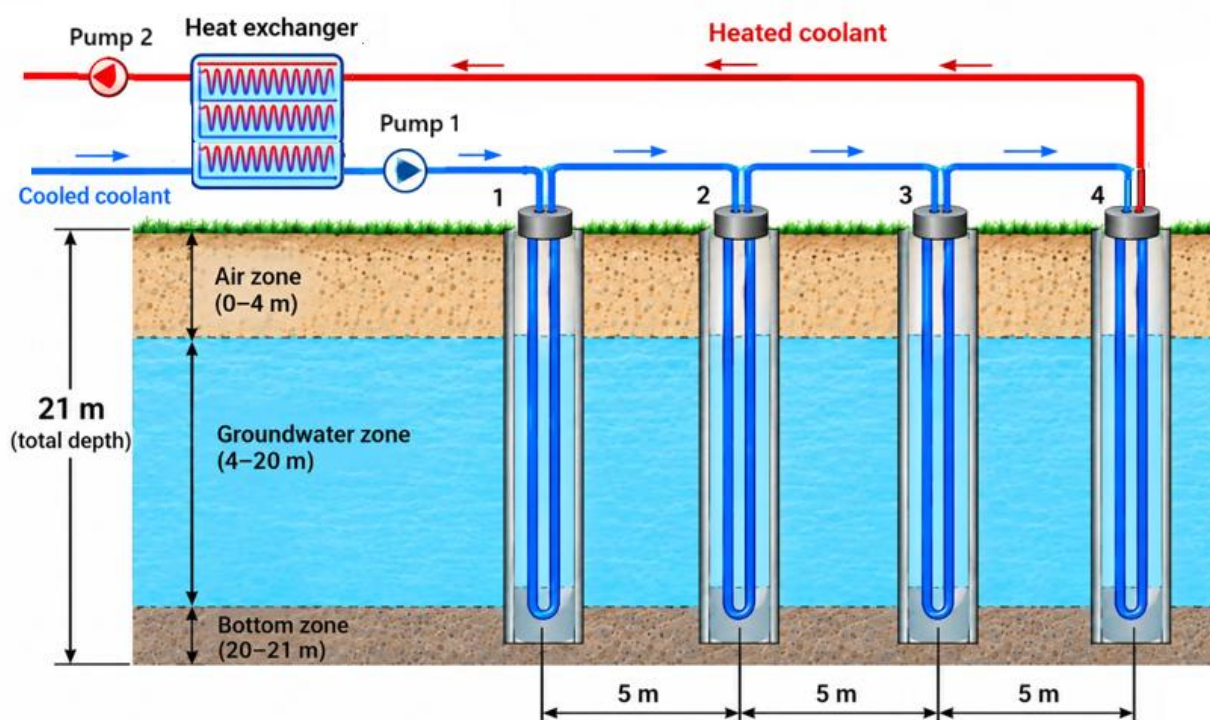


Fig.2. Scheme of a ground-source heat pump system consisting of four boreholes.

Preliminary tests have shown that the heat transfer fluid (antifreeze) can heat up to 60°C or higher during compression. Further temperature increases are undesirable, as the fluid does not have sufficient time to return to the groundwater temperature after cooling. To prevent further heating and accelerate the recovery time, it is necessary to install an automatic control system to adjust the pump pressure, thereby regulating the flow rate of the heat transfer fluid through the circuit.

3. Estimation of the thermal output of a ground source heat pump

Let us determine the amount of heat required to heat a given quantity of biomass. The bioreactor is a cylindrical vessel with a length of 2 m and a diameter of 1.44 m. The steel wall thickness is 4 mm [15, 16]. In practice, the bioreactor vessel is filled to approximately two-thirds of its volume with an organic mixture of cattle manure and water.

The volume of the biomass to be processed, accounting for the wall thickness of the cylindrical bioreactor vessel, is

$$V_w = 3,14 \times 0,68^2 \times 1,92 \times 2/3 = 1,86 \text{ m}^3$$

The amount of heat required to heat the given quantity of biomass is determined using the standard formula:

$$Q = V_w \times \rho_w \times c \times \Delta t = 1.86 \times 10^3 \times 4200 \times 30 \approx 23.436 \times 10^9 \text{ J} = 6,510 \text{ kWh}$$

where ρ_w is the density of the heat carrier and c is the specific heat capacity of water is 4,200 J/(kg·°C).

Thus, the objective is to maintain nearly 2 tons of biomass within a specified temperature range. The target heating temperature for the bioreactor's "water jacket" is +42°C, even if the ambient temperature drops to -30°C. It is common practice to use a non-freezing heat transfer fluid—ethylene glycol (ethanediol, chemical formula $C_2H_6O_2$)—in sub-zero temperatures. This is the simplest dihydric alcohol; it appears as a clear, odorless liquid with an oily consistency and a sweet taste. While the substance is highly miscible with water, it is highly toxic to humans and animals and is classified as a moderately hazardous substance (Hazard Class 3). Its key property is that it significantly lowers the freezing point of aqueous mixtures, preventing the fluid from freezing in cold conditions. The proposed technology leverages the stable temperature of groundwater (+3 to +8°C). Therefore, it is crucial to accurately calculate the parameters of the ground-loop heat exchanger's primary circuit to prevent the borehole from freezing. To determine the limiting pressure and temperature values, the thermal capacity of the ground heat exchanger based on fundamental heat balance principles, accounting for heat losses will be calculate.

In a ground-source heat pump system, the cooling of the heat transfer fluid occurs automatically as part of the system's operation. The cooling process within the expansion valve works as follows: after the fluid in the internal circuit has transferred its heat to the storage heat exchanger (at +42°C) and condensed, it passes through a thermostatic expansion valve (TXV) or throttle. At this point, the fluid pressure drops sharply, causing its temperature to plummet instantly to below-freezing levels (e.g., -2°C to -5°C). Next, thermal regeneration takes place in the ground: the "super-cooled" fluid (at 0°C) is circulated back underground to a depth of 20 meters. Since the temperature of the surrounding groundwater remains stable at +3°C or +8°C, the earth acts as a constant, reliable heat source. As the fluid flows through the underground piping, it absorbs heat from the earth, warming back up to its initial +3°C to +8°C range before returning to the pump, thereby completing the cycle.

The length of the circuit - specifically, the length of the pipes carrying the heat transfer fluid—must strictly correspond to the required heat extraction rate. In this instance, the ground-source heat pump (GSHP) circuit consists of copper U-tubes with a diameter of 32 mm, arranged in series across four boreholes 20 meters deep and filled with the heat transfer fluid (see Fig. 2).

Heat transfer per meter of pipe depends on numerous factors, such as soil type, installation depth, and the thermal conductivity of the soil and groundwater. The designed GSHP system utilizes geothermal heat from a depth of 20 meters, where the temperature is more stable than at the surface. Calculating the parameters of the GSHP primary circuit requires determining the ethylene glycol flow rate and the thermal power output needed to supply sufficient heat to warm the specified volume of biomass.

An ethylene glycol solution with a freezing point of -13°C is used as the heat transfer fluid in the primary circuit. The specific heat capacity of an aqueous ethylene glycol solution depends on its concentration and temperature, typically ranging from 3.1 to 4.1 kJ/(kg·°C). Pure water has the highest heat capacity (4.2 kJ/(kg·°C)), whereas pure ethylene glycol is approximately 2.4 kJ/(kg·°C).

For the calculation, the solution properties at 0°C are used: density is 1050 kg/m³ (1.05 g/cm³) and heat capacity is 3.94 kJ/(kg·K). When using an ethylene glycol solution, the pressure loss within the pipe is 1.5 times higher than with water. To calculate the parameters of the heat pump unit's primary circuit, it is necessary to determine the ethylene glycol flow rate.

The temperature difference is assumed to be: $\Delta T = 30^\circ\text{C}$. The loop length of each U-shaped copper pipe is 40 m, the distance between the pipes is 5 m, hence the total length of the copper pipeline with coolant is

$$L = 40\text{m} \cdot 4 + 15 = 175\text{m};$$

$$\text{Volume of pumped coolant: } V_t = 3,14 \times 0,16^2 \times 175 = 14,07 \text{ m}^3$$

When compressed, the coolant heats up; the amount of heat it transfers per unit time is equal to:

$$Q_t = V_t \times \rho \times c_t \times \Delta T = 14,07 \text{ m}^3 \times 1050 \text{ kg/m}^3 \times 3,94 \text{ kJ/(kg} \cdot ^\circ\text{C)} \times (30^\circ\text{C}) \approx 1745.81 \text{ kJ} \approx 0.489 \text{ kWh}$$

Depending on the soil type and condition (dry sand, clay, or water-saturated soil), a U-shaped geothermal probe extracts an average of 30 to 50 W of thermal energy per linear meter. The total thermal power extracted from the ground for the geothermal heat pump will be $175 \text{ m} \times 40 \text{ W/m} \approx 7 \text{ kW}$ (low-potential heat). To determine the volume of a 50% ethylene glycol solution that can be heated, we compare the thermal power of the heat pump with the flow rate of the coolant.

4. Results and discussion

For a circuit thermal output of 7 kW, the heat carrier flow rate must be very low is only about 160 liters per hour (0.044 L/s). The fluid velocity in a 32 mm pipe would then be approximately 0.07 m/s (this speed corresponds to laminar flow, which impairs heat exchange; therefore, it is more efficient to use a high-flow circulation pump while heating the system cyclically). The total length is 175 m. Assuming a heat yield q of approximately 40–50 W per linear meter of the borehole, the external circuit circulation pump speed must be adjusted so that the temperature difference (ΔT) between the outgoing and returning heat carrier is about 3°C–5°C. To set the circulation pump speed to achieve a temperature difference (ΔT) within the 3°C–5°C range, the required volumetric flow rate (V) of the coolant is calculated. Clearly, maintaining the required temperature involves costs associated with compensating for heat losses through the walls and via exhaust gases, as well as the energy required to heat the contents, etc. Heat losses through the walls and ventilation losses must be taken into account; approximately 30% should be added to the calculated value. Since there is a closed-loop ground-source heat pump (GSHP) circuit consisting of copper U-tubes filled with heat transfer fluid, the calculation is based on the thermal power that this circuit can consistently extract from the ground.

1) *Calculation of the circuit's thermal power.* Given that the total length of piping in the boreholes is 175 meters, and assuming a heat extraction rate of (40–50) W per linear meter, the total thermal power (Q) extracted from the ground by the external circuit is:

Minimum: $Q_1 = 175 \text{ m} \times 40 \text{ W/m} = 7,000 \text{ W}$ (7.0 kW)

Maximum: $Q_2 = 175 \text{ m} \times 50 \text{ W/m} = 8,750 \text{ W}$ (8.75 kW)

2) *Calculation of required flow rate.* For a propylene glycol-based heat transfer fluid (average specific heat capacity $C_p \approx 3.8 \text{ kJ/(kg} \cdot \text{°C)}$) and density $\rho = 1030 \text{ kg/m}^3$, the required flow rate is calculated using the formula:

$$V = \frac{Q}{C_p \cdot \rho \cdot \Delta T}$$

Depending on the required temperature difference for each borehole, the circulation pump must provide the following flow rates:

Target temperature difference, (ΔT_g)	With specific heat dissipation $q = 40 \text{ W/m}$ (7.0 kW)	With specific heat dissipation $q = 50 \text{ W/m}$ (8.75 kW)
at $\Delta T_g = 3^\circ\text{C}$ (max flow)	~35,8 liters per minute	~74,52 liters per minute
at $\Delta T_g = 5^\circ\text{C}$ (min flow)	21,42 liters per minute	~44, 70 liters per minute

Calculations show that the circulation pump must circulate the heat transfer fluid at a rate ranging from 21.42 to 44.7 liters per minute. In the experiments, flow meters were used to regulate pump operation within the GSHP system. Flow regulators were installed on the ground-loop distribution manifold, where the pipelines from all four boreholes converge. Since the boreholes are connected to the manifold in series, the flow meters had to be adjusted to ensure an equal volume of heat transfer fluid flowed through each of the four boreholes (approximately 5.3–11.2 l/min per borehole). Additionally, the strength limitations of the GSHP system's copper piping had to be taken into account. Copper pipes with a 32 mm diameter (commonly used in heating and air conditioning systems) have the following characteristics: operating pressure typically does not exceed 2.5–4.0 MPa (25–40 bar), whereas the burst pressure (maximum) ranges from approximately 15 to 30 MPa (150–300 bar), depending on wall thickness (1–1.5 mm) and copper hardness.

It is also necessary to consider the system's hydraulics—specifically, pressure losses. This is because, at a temperature of -8°C , a 50% ethylene glycol solution becomes highly viscous; its kinematic viscosity increases by approximately four to five times compared to water. Consequently, the flow of the heat transfer fluid through the pipes is impeded, resulting in high friction losses (dynamic pressure).

When using a standard three-speed pressure-boosting pump, in this case, a LEO dry-rotor circulation pump with a power rating of 1500 W—the system first switches to speed 2, and the heat pump compressor starts up. After 20–30 minutes of continuous compressor operation, readings are taken from the external circuit temperature sensors (at the ground loop outlet and inlet).

If the temperature difference exceeds 5°C , the pump speed must be increased. Conversely, if the temperature difference is less than 3°C , the flow rate of the heat transfer fluid can be reduced to save electricity.

This adjustment makes it possible to ensure that the length of 175 meters of the circuit through 4 wells completely covers the needs of the system without the risk of freezing of the coolant. And it helps prevent the risk of unwanted overcooling of the coolant.

4. Conclusion

Biogas production from biomass offers potential as an alternative energy source, particularly given the abundance of biomass resources in Kazakhstan. The study analyzes biogas production technologies—focusing on their results and innovative aspects—specifically for regions remote from traditional energy sources. While biogas represents an environmentally beneficial alternative for reducing emissions and managing waste, it is crucial to implement advanced technologies incorporating methane sensors and to rigorously address environmental controls within these processes. Such measures will minimize potential harm to local populations while ensuring the long-term sustainability of biogas and biomethane production and promoting the adoption of these clean energy sources.

An assessment of the thermal energy output, accounting for the efficiency characteristic of the external circuit of a ground-source heat pump is shown. Comparing the calculation results with test measurements leads to the conclusion that the capacity of the designed ground-source heat pump system comprising four 20-meter-deep boreholes is sufficient to reliably meet the requirements for cooling or heating the heat transfer fluid within the specified temperature range.

Monitoring data of the developed system operation and results of measuring its performance indicators during extended experimental testing under autumn-winter climatic conditions will be obtained. Subsequently, a more detailed analysis of heat transfer for each borehole is planned, utilizing modern software suites to determine the optimal operating parameters of the developed geothermal heat pump system.

Conflict of interest statement

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.

CRediT author statement

Sakipova S.E.: supervision, writing – review & editing; **Smagulov Zh.:** methodology, validation; **Bekturganov Zh.S., Ismailov Zh.T.:** conceptualization, investigation; **Kartbayeva, Gulnaz T.:** data curation, writing-original draft; **Duisenbayeva, M.S., Ospanova D.A.:** formal analysis, visualization. The final manuscript was read and approved by all authors.

Statement on the use of Artificial Intelligence.

The authors declare that no artificial intelligence tools were used to generate scientific content, results, or conclusions of this article.

Data Availability Statement

The data are available upon reasonable request from the authors.

Funding

This research is funded by the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan (AP26102107).

References

- 1 Kadam, R., Jo, S., Lee, J., Khanthong, K., Jang, H., & Park, J. (2024). A Review on the Anaerobic Co-Digestion of Livestock Manures in the Context of Sustainable Waste Management. *Energies*, 17(3), 546. <https://doi.org/10.3390/en17030546>
- 2 Pilarska, A. A., Pilarski, A., Pilarski, K., Pietrzak, M. B., Przybył, K., & Kałuża, T. (2026). Biogas Plants in the Sustainable Energy Transition: Environmental Performance, Public Health Implications and Socio-Economic Trade-Offs. *Sustainability*, 18(19), 9876. <https://doi.org/10.3390/su18199876>
- 3 Wang, W., Chang, J.-S., & Lee, D.-J. (2023). Anaerobic digestate valorization beyond agricultural application: Current status and prospects. *Bioresource Technology*, 373, Article 128742. <https://doi.org/10.1016/j.biortech.2023.128742>
- 4 Rowan, M., Umenweke, G.C., Epelle, E.I.; Christianah, I., Okoye, P.U., Gunes, B., Okolie, J.A. (2022) Anaerobic co-digestion of food waste and agricultural residues: An overview of feedstock properties and the impact of biochar addition. *Digit. Chem. Eng.*, 4. <https://doi.org/10.1016/j.dche.2022.100046>

- 5 Liu, Z., Gao, X., Li, Z., Yang, X., & Hu, Y. (2023). Evaluation of Biogas and Solar Energy Coupling on Phase-Change Energy-Storage Heating Systems: Optimization of Supply and Demand Coordination. *Buildings*, 13(11), 2712. <https://doi.org/10.3390/buildings13112712>
- 6 Tetteh, F., Safo, D., Laari, P. Y., Berko, M., & Osafo, L. (2025). Enhancing Biogas Production Using Organic Waste as Clean Energy for Sustainable Development. *Engineering Proceedings*, 117(1), 59. <https://doi.org/10.3390/engproc2025117059>
- 7 Sharipov, M., Majitov J., Ergashev S., Shodiyev E., Narzullayeva Z. (2025). Substitution of thermal-technical and geometrical parameters of a small-scale biogas plant. *Eurasian phys. tech. j.*, 22(3 (53), 84–90. <https://doi.org/10.31489/2025N3/84-90>
- 8 Xue, X., Lv, J., Chen, H., Xu, G., Li, Q. (2022). Thermodynamic and economic analyses of a new compressed air energy storage system incorporated with a waste-to-energy plant and a biogas power plant. *Energy*, 261, 125367. <https://doi.org/10.1016/j.energy.2022.125367>
- 9 Arslan, M., Kunt, M., & Yilmaz, C. (2023). Design and optimization of a computer simulation model for green hydrogen production by waste heat recovery from Afyon biogas plant. *International Advanced Researches and Engineering Journal*, 7(3), 157-164. <https://doi.org/10.35860/iarej.1271925>
- 10 Belyayev, Ye., Kaltayev, A., Aliuly A., Mohanraj, M., Singh, R.M. (2019). The innovation of the Republic of Kazakhstan. IP name: Hybrid solar-ground source heat pump; IP number: №33382. <https://journal.kaznaru.edu.kz/index.php/research/article/view/721> [in Russian]
- 11 Amanzholov, T., Seitov, A., Aliuly, A., Yerdesh, Y., Murugesan, M., Botella, O., Feidt, M., Wang, H. S., Belyayev, Y., & Toleukhanov, A. (2022). Thermal Response Measurement and Performance Evaluation of Borehole Heat Exchangers: A Case Study in Kazakhstan. *Energies*, 15(22), 8490. <https://doi.org/10.3390/en15228490>
- 12 Yessenzhol, D., Sakipov, K., Sharipov, M., Majitov, J., Akhmetov, S., & Imomov, S. (2026). Comparative analysis of mixing regimes in biogas plants for optimization of the stirring process. *Eurasian phys. tech. j.*, 23(2 (56), 47–56. <https://doi.org/10.31489/2026N2/47-56>
- 13 Cao, Y., Dhahad, H.A., Togun, H., Haghighi, M.A., Anqi, A.E., Farouk, N., Rosen, M.A. (2021). Seasonal design and multi-objective optimization of a novel biogas-fueled cogeneration application. *Int. J. Hydrogen Energy*, 46(42), 21822–21843. <https://doi.org/10.1016/j.ijhydene.2021.04.044>
- 14 Kartbayeva, G.T., Nusupbekov, B.R., Khasenov, A.K., Nusupbekov, U.B., Karabekova, D.Zh., Zholdasbek, E.A. (2022). Installation for biogas and biofertilizer from certain waste. Patent for utility model No. 6971, 4 p. Published 01.04.2022. [in Russian] <https://gosreestr.kazpatent.kz/Utilitymodel/Details?docNumber=354140>
- 15 Sakipova, S., Smagulov, Z., Nussupbekov, B., Ismailov, Z., Duisenbayeva, M., Nussupbekov, U., & Turlybekova, R. (2026). Improvement of a Combined Heating System for a Bioreactor Designed for Biogas Production Using Coal–Water Fuel. *Energies*, 19(14), 3408. <https://doi.org/10.3390/en19143408>.
- 16 Smagulov, Zh.K., Bekturganov, Zh.S., & Ismailov, Zh.T. (2026). Bioreactor for processing organic waste using renewable energy sources. Patent 2025/1858.2, Bulletin 7, 5. Published 20.02.2026. [in Russian] <https://gosreestr.kazpatent.kz/Utilitymodel/Details?docNumber=442842>

AUTHORS' INFORMATION

Sakipova, Saule E. – Candidate of Phys.& Math. Sciences, Professor, Department of Engineering Thermophysics named after professor Zh.S. Akylbayev, Buketov Karaganda National Research University, Karaganda, Kazakhstan; [Scopus Author ID: 6504154211](#); <https://orcid.org/0000-0002-7505-8413>; sakipova1607@gmail.com;

Smagulov, Zhanaidar K. – Candidate of Phys.& Math. Sciences, Professor, Department of Radiophysics and Electronics, Buketov Karaganda National Research University, Karaganda, Kazakhstan; [Scopus Author ID: 6506808882](#); <https://orcid.org/0000-0002-3412-973X>; smagul@mail.ru

Bekturganov, Zhanaly S. – Doctor of Chemical Sciences, Professor, Department of Radiophysics and Electronics, Buketov Karaganda National Research University, Karaganda, Kazakhstan; [Scopus Author ID: 6507538959](#); <https://orcid.org/0000-0002-6487-7835>; zhbekturganov@gmail.com

Ismailov, Zharaskan T. – Candidate of Phys.& Math. Sciences, Professor, Department of Radiophysics and Electronics, Buketov Karaganda National Research University, Karaganda, Kazakhstan; [Scopus Author ID: 25025774800](#); <https://orcid.org/0009-0002-6245-7690>; Zhismailov@yandex.kz;

Kartbayeva, Gulnaz T. – Candidate of Biological Sciences, **Assoc. Professor**, Buketov Karaganda National Research University, Karaganda, Kazakhstan; [Scopus Author ID: 57197772178](#); <https://orcid.org/0000-0003-1860-3734>; gulnaz_kartbayeva@mail.ru

Duisenbayeva, Moldir – Ph.D., Head of the Department of Physics, Abylkas Saginov Karaganda Technical University, Karaganda, Kazakhstan; [Scopus Author ID: 60761103800](#); <https://orcid.org/0000-0003-3733-7662>; m_o_l_d_i_r_89@mail.ru

Ospanova, Didar A. – Ph.D., Senior Lecture, Department of Engineering Thermophysics named after professor Zh.S. Akylbayev, Buketov Karaganda National Research University, Karaganda, Kazakhstan; [Scopus Author ID: 56286193500](#); <https://orcid.org/0000-0001-7243-4965>; bota_didar@mail.ru