Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Performance evaluation of a small-capacity biogas digester using mixed agricultural waste under mesophilic conditions

Samir Orujov

samir.orujov@sdu.edu.az

Sumgayit State University

Muzaffar Murodov

Namangan State Technical University

Vagif Hasanov

Azerbaijan Technical University

Ilnur Kh. Gayfullin

Kazan State Agrarian University

Avazbek Akhmedov

Namangan State Technical University

Ghadder Ghabour

Damascus University

Mohamad Amir Hababa

Damascus University

Research Article

Keywords: anaerobic digestion, household-scale biogas digester, agricultural waste, methane concentration, energy assessment, energy efficiency, sustainable energy services, economic analysis

Posted Date: November 25th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-11854276/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: The authors declare no competing interests.

Performance evaluation of a small-capacity biogas digester using mixed agricultural waste under mesophilic conditions

Murodov Muzaffar Khabibullaevich[1] , Vagif Hasanov[2] , Ilnur Kh. Gayfullin[3] , Samir Orujov[4], Akhmedov Avazbek Bokhodir ogli[5], Ghadder Ghabour [6], Mohamad Amir Hababa[7]

Abstract

Household-scale biogas systems offer an environmentally sustainable solution for renewable energy production and agricultural waste management in rural areas; however, their widespread application is often limited by high construction costs and insufficient performance evaluation. This study presents the design, fabrication, and experimental assessment of a manually mixed household biogas digester with a fabrication cost of approximately USD 100, operated under mesophilic conditions using locally available agricultural residues. Following initial batch operation, daily supplementary feeding of 4.5 L began on 17 August 2026.

Mean daily biogas production on 18-20 August 2026 was 0.220 ± 0.002 m³/day (mean ± sample standard deviation; n = 3), and gas analysis indicated a methane volume fraction of 60.0%. Substrate pH measurements ranged from 6.8 to 7.3. The calculated gross energy potential was approximately 1.31 kWh/day. Assuming unchanged production over 365 operating days, this corresponds to approximately 479 kWh/year and a gross energy equivalent of 37.2 kg of LPG.

Under the assumed year-round production and zero annual operating expenditure, the fuel-only simple payback period was approximately 2.35 years at private-market LPG prices and 15.0 years at subsidized prices. For an illustrative five-year payback target, the minimum daily biogas production was 0.103 and 0.659 m³/day, respectively. These estimates represent gross fuel-energy equivalence and exclude digestate revenue.

The study combines experimental digester performance with fuel-price-dependent economic thresholds for household biogas use in Uzbekistan. At the reported production level, the system meets the illustrative five-year simple payback criterion under private-market LPG prices, whereas subsidized prices require a higher daily gas output. These findings identify the production and fuel-price conditions governing investment recovery under the stated assumptions.

Keywords: anaerobic digestion; household-scale biogas digester; agricultural waste; methane concentration; energy assessment; energy efficiency; sustainable energy services; economic analysis.

[1] *Associate professor, Department of Power Engineering, Namangan State Technical University, Namangan, Uzbekistan.*
[2] *Professor, Head of the Department of Energy Efficiency and Green Energy Technologies, Azerbaijan Technical University, Baku, Azerbaijan*
[3] *Associate Professor of Kazan State Agrarian University, 65, Karla Marksa str., Kazan, 420015, Russia*
[4] *Department of Scientific Research and Technological Transfer, Sumgayit State University, Sumgayit, Azrebaijan,*
Corresponding author: samir.orujov@sdu.edu.az
[5] *PhD student, Department of Power Engineering, Namangan State Technical University, Uzbekistan.*
[6] *PhD student, Electrical Energy Engineering, Damascus University, Damascus, Syria*
[7] *PhD student, Electrical Energy Engineering, Damascus University, Damascus, Syria*

1. Introduction

The increasing demand for sustainable and decentralized energy solutions has intensified global interest in biogas technology as an effective approach for converting agricultural waste into renewable energy while simultaneously addressing waste management challenges (Kothari, R., et al. 2010) Anaerobic digestion of organic residues offers multiple benefits, including biogas production for energy generation and the generation of organic fertilizer suitable for agricultural use [2; 3]. As a result, biogas systems are increasingly recognized as a key component of circular economy and sustainable rural development strategies [4].

Agricultural waste, particularly animal manure and crop residues, represents one of the most widely available feedstocks for anaerobic digestion [5]. Numerous studies have demonstrated that co-digestion of different agricultural substrates can enhance process stability and biogas yield by improving nutrient balance and the carbon-to-nitrogen ratio [6; 7]. Under mesophilic conditions (35-37 °C), anaerobic digestion of mixed agricultural waste has been reported to produce biogas with methane content typically ranging from 50% to 70%, depending on substrate composition and operating conditions [2; 8]. Consequently, mesophilic digestion remains the most commonly applied approach due to its operational stability and relatively low energy demand [8].

Household biogas digesters have been developed using different construction materials and configurations to accommodate local resource availability and operating requirements [10; 11]. Their adoption depends on investment cost, feedstock availability, maintenance requirements, and compatibility with household energy needs [10; 12]. Evaluating these factors together with recorded gas production can help establish the practical operating requirements and economic prospects of a locally fabricated system.

Previous studies have examined household digester construction, materials, and implementation in developing countries [10; 12] . These studies provide a basis for evaluating locally fabricated systems in terms of their operating performance, material requirements, and potential household benefits [13]. For a specific installation, the practical value of biogas production depends on both the measured gas output and the cost of the conventional fuel it can replace. Accordingly, the present assessment links digester performance with LPG-equivalent energy output and evaluates the sensitivity of simple payback to two fuel-price scenarios in Uzbekistan.

This study evaluates a locally fabricated, manually mixed biogas digester with a total volume of 0.20 m³ and a working volume of 0.15 m³, operated under mesophilic conditions with a mixture of sheep manure, rabbit manure, poultry waste, and fodder residues. The assessment combines biogas production records, gas composition measurements, and pH observations with estimates of gross energy output and LPG-equivalent fuel displacement. Economic performance is examined under subsidized and private-market LPG prices in Uzbekistan to determine how fuel pricing affects the simple payback period. The study provides an experimental case assessment of the digester and identifies the operating and economic factors relevant to its household application.

2. Materials and methods

2.1. Reactor Design and Construction

The digester was fabricated from a vertically installed cylindrical metal vessel with a total volume of 0.20 m³ and a wall thickness of 0.8 mm. The working substrate volume was 0.15 m³, leaving a nominal headspace of 0.05 m³. A rubber gasket was fitted around the lid circumference to seal the lid-vessel joint. The reactor configuration and associated gas collection components are shown in Fig. 1. The main components of the digester and their functions are summarized in Table 1.

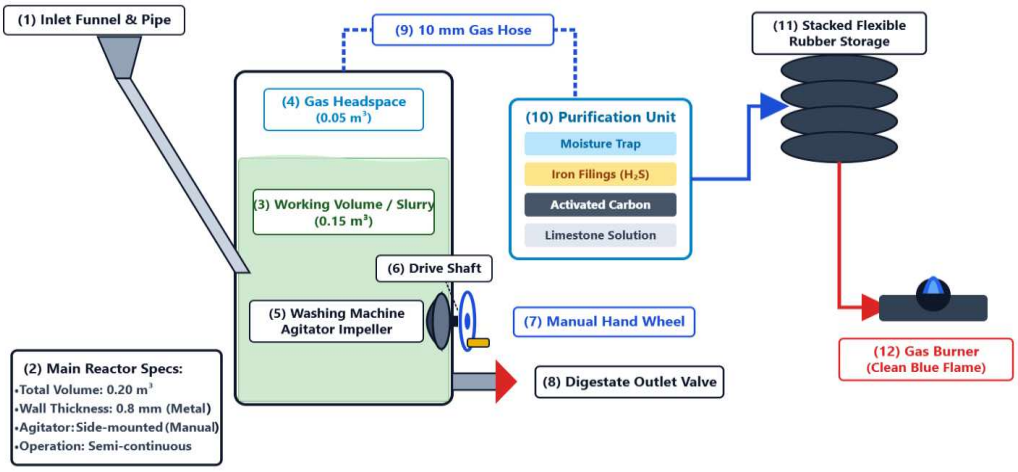


Figure 1. Schematic diagram of the 0.2 m³ small-capacity vertical biogas digester system with side-mounted agitator: (1) Feedstock inlet funnel and pipe; (2) Main cylindrical reactor body (0.2 m³ total volume); (3) Liquid slurry / working volume (0.15 m³); (4) Gas accumulation headspace (0.05 m³); (5) Side-mounted washing machine agitator impeller; (6) Drive shaft; (7) External manual hand wheel; (8) Digestate discharge valve; (9) Flexible 10 mm gas delivery hose; (10) Multistage biogas purification unit; (11) Stacked flexible rubber storage chambers; (12) Gas burner unit.

Table 1. Main components and functional descriptions of the biogas digester.

Item No.	System Component	Technical Specification / Functional Description
1	Inlet Funnel & Pipe	Slanted feeding tube with funnel for daily substrate loading
2	Reactor Body	Thin-walled (0.8 mm) vertical cylindrical metal vessel (Total volume: 0.20 m^3)
3	Digestion Zone	Effective liquid working volume of 0.15 m^3 (75% of total volume)
4	Gas Headspace	Gas collection zone of 0.05 m^3 (25% headspace)
5	Agitator Impeller	Side-mounted washing machine impeller installed near the bottom section
6	Drive Shaft	Stainless steel connecting shaft transferring torque from external hand wheel to internal impeller.
7	Manual Hand Wheel	External hand wheel directly coupled to the side-mounted impeller for periodic manual mixing (3 × 10 min/day)
8	Digestate Outlet	Bottom-mounted outlet pipe fitted with a manually operated valve for digestate discharge corresponding to the daily feed volume.
9-10	Purification System	Gas treatment unit comprising a moisture trap, iron filings, activated carbon, and an aqueous suspension of slaked lime ($Ca(OH)_2$).
11-12	Storage & Burner	Stacked flexible rubber storage chambers connected to a household gas cooker

Mixing was performed using a side-mounted impeller adapted from a conventional washing machine agitator and installed near the lower part of the vessel (Fig. 1). The impeller was connected through a shaft to an external hand wheel and operated manually three times daily for 10 min per session. This arrangement required no electrical power for mixing. The mixing schedule was intended to redistribute the substrate and limit settling and surface scum formation, consistent with the functions of mixing described in the literature [14].

Biogas was conveyed from the reactor headspace through a flexible gas hose with a diameter of 10 mm. Flexible rubber chambers connected to the gas collection line were used for temporary storage before utilization. These chambers were selected for their local availability and low acquisition cost. Below, the completed reactor is shown in its operational configuration, including the vertical metal vessel, gas outlet connection, mechanical mixing system, and airtight rubber-sealed lid (Fig.2).



Figure 2. Assembled 0.2 m^3 small-capacity vertical biogas digester.

2.2. Feedstock Composition and Preparation

The substrate used in this study consisted of a multi-component agricultural waste mixture, prepared in equal proportions (1:1:1:1) by mass. The feedstock included:

- Sheep manure
- Rabbit manure
- Poultry waste
- Fodder residues

The four feedstock components were combined in equal proportions by mass and diluted with water before loading into the digester (Fig. 3). The 1:1:1:1 ratio describes the feedstock preparation recipe. Assessment of the resulting nutrient balance requires the total solids, carbon, and nitrogen contents of the individual components, which are relevant to evaluating agricultural waste co-digestion [6; 15].



Figure 3. The substrate with a mixed composition and loaded into the bioreactor.

Daily supplementary feeding began on 17 August 2026 to sustain biogas production. The daily feed volume was 4.5 L, with a measured mass of 4.7 kg. During daily feeding, approximately 4.5 L of digestate was discharged by manually opening the valve on the bottom outlet pipe, maintaining a working volume of approximately 0.150 m^3. Total solids (TS) were determined gravimetrically by drying a sample of the prepared feed at 105 °C to constant mass. The dried sample was subsequently ignited in a muffle furnace at 550 °C for at least 2 h. Volatile solids (VS) were calculated from the mass lost during ignition and expressed as a percentage of TS. Analysis of a single prepared-feed sample gave a TS content of 12% of wet mass and a VS content of 10% of TS. These values were used to calculate the daily VS input and organic loading rate. The daily volatile solids input was calculated from the measured daily feed mass and the laboratory-determined TS and VS fractions:

$$\dot{m}_{\mathrm{VS,in}} = m_{\mathrm{feed,d}}\, w_{\mathrm{TS}}\, w_{\mathrm{VS/TS}} = 4.7 \times 0.12 \times 0.10 = 0.0564\ \mathrm{kg\,VS/day}. \quad (1)$$

The organic loading rate was calculated relative to the reactor working volume:

$$\mathrm{OLR} = \frac{\dot{m}_{\mathrm{VS,in}}}{V_{\mathrm{working}}} = \frac{0.0564}{0.150} = 0.376\,\mathrm{kg\,VS/(m^3 \cdot day)}. \quad (2)$$

Here, $m_{\mathrm{feed,d}}$ is the daily wet feed mass (kg/day), w_{TS} is the TS mass fraction of the wet feed, $w_{\mathrm{VS/TS}}$ is the VS mass fraction of TS, and V_{working} is the reactor working volume (m^3).

The nominal hydraulic retention time, calculated from the working volume and daily volumetric feed rate, was approximately 33.3 days. The feed characteristics and calculated loading parameters for the supplementary-feeding period are summarized in Table 2.

Table 2. Feed characteristics and calculated loading parameters during supplementary feeding.

Parameter	Value	Basis
Daily feed volume	4.5 L/day	Reported feeding volume
Daily feed mass	4.7 kg/day	Measured by weighing
Feed density	1.044 kg/L	Calculated from feed mass and volume
Total solids (TS)	12% of wet mass	Laboratory measurement of a single prepared-feed sample
Volatile solids (VS/TS)	10% of TS	Loss on ignition of the dried residue from the same sample
VS content on a wet-mass basis	1.2%	Calculated: 0.12 × 0.10
Daily TS input	0.564 kg TS/day	Calculated: 4.7 × 0.12
Daily VS input	0.0564 kg VS/day	Calculated: 4.7 × 0.12 × 0.10
Reactor working volume	0.150 m^3	Working substrate volume
Organic loading rate (OLR)	0.376 kg VS/(m^3·day)	Daily VS input / working volume
Nominal hydraulic retention time (HRT)	33.3 days	Working volume / daily feed volume

Note: *TS is expressed relative to the wet feed mass, whereas VS is expressed relative to TS. Digestate was discharged manually through the bottom outlet valve in an amount corresponding to the daily feed volume.*

2.3. Operating Conditions

The anaerobic digestion process was conducted under mesophilic conditions, with the reactor temperature maintained in the range of 35-37 °C, which is widely recognized as the optimum temperature range for stable methane production and microbial activity [8]. Manual mechanical mixing was performed using an externally operated hand-driven mechanism connected through a common shaft to an internal drum-type agitator. Mixing was applied three times per day, with each cycle lasting 10 min, to prevent sedimentation and improve mass transfer [14]. The manually operated system required no electrical energy for agitation.

Process pH was periodically measured using a portable digital pH meter (PH60, Apera Instruments). Measurements were performed at three representative stages of the digestion process: during the initial phase, the stable biogas production phase, and at the end of the experimental period. The measured pH values were 6.8, 7.1, and 7.3, respectively. These measurements were used to evaluate the evolution of the acid-base conditions and the stability of the anaerobic digestion process. The pH measurements were performed on collected samples at approximately 25 °C, whereas the digester itself was operated under mesophilic conditions at 35-37 °C.

Biogas volume was measured downstream of the gas treatment unit using a RITTER TG 0.5 drum-type gas meter (Fig. 4). Reported volumes were obtained directly from differences between cumulative meter readings and represent treated gas at the measurement conditions, without correction to a dry-gas reference temperature and pressure. Cumulative meter readings were recorded at 08:00 and 20:00, and daily biogas volumes were calculated by summing the increments over two consecutive 12-hour intervals. The gas temperature at the meter was 25 °C at both daily reading times (08:00 and 20:00). Daily volumes recorded from 18 to 25 August 2026 are reported in Section 3.1. The mean daily biogas volume used in the energy calculations was calculated from the measurements recorded on 18-20 August 2026. Combustion tests were additionally performed to qualitatively assess the flammability of the produced biogas. The main operating parameters are summarized in Table 3.





Figure. 4. RITTER TG 0.5 drum-type gas meter used for biogas volume measurements.

Table 3. Operating parameters of the small-capacity biogas digester.

Parameter	Value	Unit / Description
Reactor type	Vertical, mechanically mixed	-
Total reactor volume	0.20	m^3
Effective working volume	0.15	m^3
Reactor material	Thin-walled metal	0.8 mm thickness
Operating temperature	35-37	°C (mesophilic)
Feeding mode	Semi-continuous	Daily feeding
Substrate composition	Sheep, rabbit, poultry manure + fodder residues	1:1:1:1 (by mass)
Organic loading rate (OLR)	0.376	kg VS/(m^3·day)
Mixing regime	3 × 10	min/day
Start-up period	~10	days
Average biogas production	0.22 ± 0.002	m^3/day

2.4. Biogas Composition Analysis

The composition of the produced biogas was quantitatively analyzed using a portable multicomponent gas analyzer (Multitec® 545, Hermann Sewerin GmbH, Germany). The instrument was used to determine the concentrations of the principal gaseous components, including methane (CH_4), carbon dioxide (CO_2), oxygen (O_2), and hydrogen sulfide (H_2S).

Biogas composition was measured during the period of relatively consistent daily gas production. Hydrogen sulfide (H_2S) concentrations were measured at the inlet and outlet of the gas treatment unit.

The analyzer was connected to the biogas collection system through a gas sampling line, and measurements were recorded after the displayed concentrations had stabilized. This procedure minimized the influence of transient fluctuations and enabled representative characterization of the produced biogas.

Methane, carbon dioxide, and oxygen concentrations were expressed as volume percentages (vol.%), whereas hydrogen sulfide concentration was recorded in parts per million (ppm). The measured biogas composition was subsequently used to evaluate biogas quality and estimate the energy potential of the developed small-capacity digestion system.

2.5. Biogas Utilization and Digestate Observation

Before use, the produced biogas passed through a treatment unit comprising a moisture trap, iron filings, activated carbon, and an aqueous suspension of slaked lime ($Ca(OH)_2$). Combustion tests were performed using a standard gas burner.

The developed small-capacity biogas system was intended primarily to supply cooking fuel for a rural household of approximately 5-6 persons. The produced biogas was supplied directly for household cooking purposes. During periods when biogas production exceeded immediate consumption, the surplus gas was temporarily stored in flexible rubber chambers connected to the gas collection line (Fig. 5). This simple low-pressure storage approach was selected because of its low cost, local availability, and compatibility with the decentralized household-scale application of the developed system.



Figure 5. Temporary storage of surplus biogas in flexible rubber chambers connected to the small-capacity digester

Digestate samples were collected periodically. Their consistency and appearance were assessed visually, and odor was assessed qualitatively.

The appearance of the digestate obtained from the reactor is shown in Fig. 6.



Figure 6. Liquid digestates produced after anaerobic digestion of mixed agricultural waste.

3. Results and discussion

3.1. Biogas Production Performance

Biogas production commenced approximately 10 days after reactor start-up, indicating successful microbial adaptation under mesophilic conditions (Goux, X., Calusinska, et al. 2016). Following the onset of gas production, daily biogas generation gradually increased and reached a stable level after approximately 5-6 days of operation. Figure 7 shows the daily biogas volumes recorded over the monitoring period. The mean daily biogas production used in the energy calculations was calculated from the measurements recorded on 18-20 August 2026.

From 18 to 25 August 2026, daily biogas production ranged from 218 to 222 L/day (Fig. 7). Mean daily production over 18–20 August was 0.220 ± 0.002 m³/day (mean ± sample standard deviation; n = 3). From 21 to 25 August, daily production remained within 219-222 L/day.

Daily supplementary feeding began on 17 August 2026. Based on the measured feed mass and laboratory-determined solids fractions, the daily VS input was 0.0564 kg VS/day, corresponding to an organic loading rate of 0.376 kg VS/(m³·day), as calculated in Section 2.2 and summarized in Table 2. Biogas recorded during 18-20 August was produced from both the material remaining from the initial loading and the supplementary feed. Accordingly, the measured gas production is reported as daily reactor output; determination of a feed-normalized specific yield requires a longer monitoring period and a substrate mass balance accounting for the initial loading and subsequent feeding.

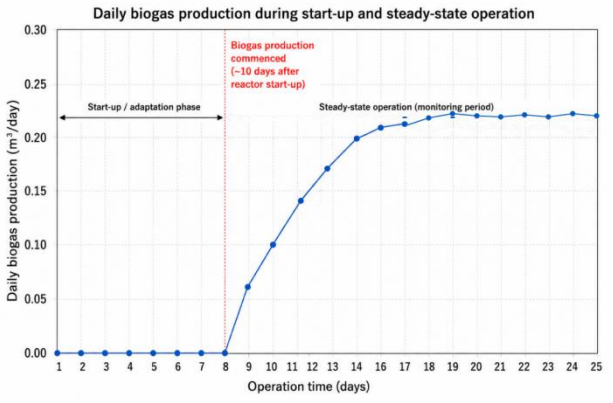


Figure 7. Daily biogas volumes recorded during the monitoring period.

Arias et al. (Arias, D. E., Veluchamy, et al. 2021) evaluated biogas production from swine manure and corn stover in a mesophilic plug-flow reactor under different organic loading rates and feed solids contents. Comparison with the present study therefore focuses on feedstock composition, reactor configuration, and operating conditions, as summarized in Table 4.

Table 4. Feedstocks, reactor configurations, and operating conditions in the present study and selected published studies

Study	Feedstock	Reactor configuration	Operating conditions
This study	Sheep manure, rabbit manure, poultry waste, and fodder residues	Locally fabricated, manually mixed digester (0.20 m³ total volume; 0.15 m³ working volume)	Mesophilic (35-37 °C); semi-continuous feeding; organic loading rate of – OLR = 0.376 kg VS/(m³·day) during supplementary feeding
Abd Allah et al. [18]	Cattle manure and milled corn stover	Family-scale digester	Co-digestion under cold-climate conditions
Ahlberg-Eliasson et al. [19]	Cattle manure alone or mixed with poultry manure	Continuously stirred tank reactors	Different organic loading rates and mesophilic and thermophilic temperatures
Arias et al. [20]	Swine manure and corn stover	Anaerobic plug-flow reactor	Mesophilic co-digestion at different organic loading rates and feed solids contents

The studies summarized in Table 4 provide context for the feedstock mixtures and reactor configurations used in small-scale anaerobic digestion [19; 21]. In the present experiment, supplementary feeding began shortly before the selected gas-production measurements. The results therefore characterize reactor output during the transition from initial batch operation to daily feeding. Longer-term monitoring under a consistent feeding regime would support evaluation of sustained production and feed-normalized biogas yield.

3.2. Mixing and Feeding Regime

The digester was operated with manual mixing three times daily for 10 min per session and daily substrate feeding. The reported biogas production therefore characterizes the combined operation of this mixing schedule, feeding regime, and substrate mixture. Mixing was intended to redistribute the substrate and promote contact between microorganisms and organic matter, consistent with the functions described in previous studies [14; 22]. Semi-continuous feeding provided

regular substrate input [23]. The individual contributions of mixing and feeding frequency to gas production would require comparison under otherwise equivalent operating conditions.

3.3. Biogas Quality Assessment

After treatment, the biogas contained 60.0 vol.% CH_4, 38.0 vol.% CO_2, and 1.5 vol.% O_2 (Fig. 8).

The treatment unit included a moisture trap, iron filings, activated carbon, and an aqueous suspension of slaked lime ($Ca(OH)_2$).

The measured hydrogen sulfide (H_2S) concentration decreased from 5,000 ppm at the inlet to approximately 500 ppm at the outlet, corresponding to a reduction of approximately 90%.



Figure 8. Post-treatment biogas composition readings displayed on the Multitec® 545 gas analyzer.

The measured methane fraction of 60.0 vol.% was within the range of 50–70 vol.% reported for biogas from agricultural residues and animal manure under mesophilic conditions [2; 8]. The methane content and the burner test (Fig. 9) support the potential use of the treated biogas as a cooking fuel. Emissions and indoor exposure under household cooking conditions were not evaluated in this study.

The measured O_2 fraction was 1.5 vol.%. Air ingress during sampling or temporary gas storage is one possible explanation [25]. The source of the measured O_2 was not determined in this study.

The outlet measurement showed that residual H_2S remained after treatment. The combustion test assessed whether the treated biogas could sustain a flame. Evaluating its suitability for household use would require separate measurements of emissions and indoor exposure.

The treated biogas produced a blue flame during the combustion test (Fig. 9). This observation confirmed that the gas could be ignited and sustain a flame under the test conditions.



Figure 9. Blue flame observed during the combustion test of the treated biogas.

The measured methane fraction was used to estimate the energy content of the biogas and the equivalent quantity of LPG on a fuel-energy basis.

3.4. pH Evolution and Process Stability

Figure 10 shows the substrate pH measured at three stages of digester operation.



Figure 10. Evolution of substrate pH during the initial phase, stable biogas production phase, and final stage of the anaerobic digestion experiment.

The substrate pH increased from 6.8 at the initial sampling to 7.1 at the intermediate sampling and 7.3 at the final sampling (Fig. 10). These measurements describe the pH at the three sampling points. Assessing whether volatile fatty acids accumulated during operation would require direct measurements of their concentrations.

The measured pH range of 6.8-7.3 was consistent with conditions generally considered favorable for methanogenic activity [8]. Further characterization of alkalinity and volatile fatty acid concentrations would help explain the observed pH changes and assess the buffering behavior of the substrate.

Taken together, the three pH measurements, recorded daily biogas volumes, and measured methane concentration describe the digester's performance during the observation period. Longer-term monitoring of these indicators, together with alkalinity and volatile fatty acid measurements, would support assessment of process stability under continued daily feeding.

3.5. Digestate Characteristics and Utilization Potential

The digestate appeared homogeneous and liquid, and its odor was qualitatively perceived as less intense than that of the feedstock. These observations describe its physical appearance and perceived odor. Assessment of its potential use as a fertilizer requires measurements of nutrient content and other relevant physicochemical and microbiological properties [17].

Agricultural use of digestate offers a potential route for recycling nutrients from the feedstock and complements energy recovery within a circular bioeconomy [3; 17]. For the present system, this potential should be assessed using digestate characterization and application trials.

Further assessment should quantify total solids and nitrogen, phosphorus, and potassium concentrations, examine microbiological quality, and evaluate plant responses in controlled application trials. These results would help determine appropriate application rates and the potential fertilizer replacement value of the digestate.

3.6. Energy Performance Assessment

The energy assessment used the mean daily biogas production of 0.220 m³/day measured on 18-20 August 2026 and a measured methane volume fraction of 60.0%. The corresponding daily methane volume was calculated as follows:

$$VCH_4 = V_{biogas} \times xCH_4 \quad (3)$$

where VCH_4 is the daily methane production (m³/day), V_{biogas} is the average daily biogas production (m³/day), and xCH_4 is the volumetric methane fraction in the produced biogas.

$$VCH_4 = 0.22 \times 0.60 = 0.132\ m^3/day$$

Using the lower heating value (LHV) of methane (35.8 MJ/m³), which is commonly adopted for energy calculations in anaerobic digestion studies (Ihász, R., & Laza, T. (2017), the gross daily energy potential of the produced biogas was estimated as:

$$E_{biogas} = VCH_4 \times LHV_{CH_4} \quad (4)$$

where E_{biogas} is the gross energy potential of the produced biogas (MJ/day), and LHV_{CH_4} is the lower heating value of methane (MJ/m³).

$$E_{biogas} = 0.132 \times 35.8 = 4.73\ MJ/day$$

The estimated gross energy content of the biogas was 1.31 kWh/day. At this daily production rate, the projected energy content was 39.4 kWh over 30 operating days and 479 kWh over 365 operating days.

To evaluate the practical significance of this energy output for rural household cooking, the biogas energy was compared with liquefied petroleum gas (LPG), which is commonly used as a cooking fuel in rural households. Assuming a lower heating value (LHV) of 46.4 MJ/kg for liquefied petroleum gas (LPG), which is commonly adopted in international energy and emission calculations [28], the daily LPG-equivalent fuel displacement was calculated as:

$$m_{LPG,eq} = \frac{E_{biogas}}{LHV_{LPG}} \quad (5)$$

where $m_{LPG,eq}$ is the equivalent mass of LPG displaced by the produced biogas (kg/day), and LHV_{LPG} is the lower heating value of LPG (MJ/kg).

$$m_{LPG,eq} = \frac{4.73}{46.4} = 0.102\ kg/day$$

On a gross fuel-energy basis, the estimated biogas output was equivalent to 3.05 kg of LPG over 30 operating days and 37.2 kg over 365 operating days. The annual estimate assumes that the mean daily biogas production measured on 18–20 August 2026 and the measured methane fraction remain constant throughout the 365 operating days. For a cylinder containing 20 kg of LPG, this annual estimate corresponds to approximately 1.86 cylinder fillings.

For an illustrative household consuming 20 kg of LPG over 30 days, the estimated biogas output was equivalent to 3.05 kg of LPG, or about 15.3% of the household's LPG fuel energy over the same period.

It should be noted that the calculated values represent gross fuel-energy equivalence and do not account for differences in burner efficiency or heat-transfer efficiency between biogas and LPG. Therefore, the results should be interpreted as an energy-potential comparison rather than a direct measurement of end-use thermal efficiency.

3.7. Economic Performance Assessment

The economic assessment considered the initial fabrication cost and the potential fuel-cost savings from LPG substitution. The reported fabrication cost of the digester system, excluding the gas burner, was approximately USD 100. Feedstocks were obtained from locally generated residues, and no feedstock purchase or transportation expenditure was reported. Mixing was performed manually, and no active heating was used during the experiment. The initial payback scenarios assumed zero annual operating expenditure; maintenance, gas-cleaning materials, and labour were identified as additional cost components for subsequent assessment. Digestate was excluded from the monetary benefit calculation.

The annual fuel-related economic benefit was estimated based on the LPG-equivalent fuel displacement calculated in Section 3.6. The produced biogas was equivalent to approximately 37.2 kg of LPG, equivalent to 1.86 household LPG cylinders (20 kg each). Two LPG price scenarios were evaluated to reflect the prevailing fuel-supply conditions in the study region and to assess the sensitivity of the economic performance to local fuel-pricing mechanisms.

Under the subsidized pricing scenario, a subsidized 50 L household cylinder containing 20 kg of LPG was supplied through district gas distribution services at a price of 43,000 UZS per filling. The annual fuel-cost saving under the subsidized LPG pricing scheme was calculated as follows:

$$B_{LPG,sub} = N_{cyl} \times P_{sub} \quad (6)$$

$$B_{LPG,sub} = 1.86 \times 43{,}000 = 79{,}980\ UZS/year$$

In the second scenario, the local market price at private LPG filling stations was 7,000 UZS/L. Assuming an average LPG density of 0.51 kg/L, the annual displacement of 37.2 kg LPG corresponded to approximately 72.9 L. The resulting annual market-price fuel saving was therefore:

$$B_{LPG,market} = V_{LPG} \times P_{market} \quad (7)$$

$$B_{LPG,market} = 72.9 \times 7{,}000 = 510{,}300\ UZS/year$$

Under the daily feeding regime, approximately 4.5 L of digestate was discharged through the bottom outlet by manually opening the valve to maintain an approximately constant working volume. Assuming the same daily discharge volume over 365 operating days, the projected annual digestate volume is 1,642.5 L. This estimate represents an extrapolation of the operating schedule rather than a measured annual output.

Digestate may provide an additional resource-recovery benefit through agricultural use. Quantifying this benefit requires measurements of digestate production, total solids, plant-available nutrient content, and suitability for the intended application. Its economic value should be assessed against the fertilizer inputs it can replace, accounting for storage, transport, and application costs. A monetary value was therefore not assigned to digestate in the present economic assessment.

The simple payback period (SPP), considering only the direct economic benefit from LPG substitution, was calculated as follows:

$$SPP = \frac{C_{initial}}{B} \quad (8)$$

where:

SPP – simple payback period (years);

$C_{initial}$ – initial investment cost (UZS);

B – annual economic benefit (UZS/year).

The resulting payback periods for the two pricing scenarios are presented below.

Under the subsidized LPG pricing scenario:

$$SPP = \frac{1{,}197{,}390}{79{,}980} = 14.97 \approx 15.0\ years$$

Under the private-market LPG pricing scenario:

$$SPP = \frac{1{,}197{,}390}{510{,}300} = 2.35\ years$$

To assess the minimum daily biogas production required to recover the initial investment within a specified period, the simple payback relationship was rearranged as follows:

$$V_{\mathrm{biogas,min}} = \frac{C_0/T + C_{\mathrm{op,yr}}}{D\, x_{\mathrm{CH_4}}\, (LHV_{\mathrm{CH_4}}/LHV_{\mathrm{LPG}})\, p_{\mathrm{LPG}}}. \quad (9)$$

Here, $V_{\mathrm{biogas,min}}$ is the minimum daily biogas production, m³/day; C_0 is the initial investment, UZS; T is the target simple payback period, years; $C_{\mathrm{op,yr}}$ is annual operating expenditure, UZS/year; D is the number of operating days per year; $x_{\mathrm{CH_4}}$ is the methane volume fraction; and p_{LPG} is the LPG price, UZS/kg. The lower heating values of methane and LPG are expressed in MJ/m³ and MJ/kg, respectively. Gas volume and methane heating value must refer to the same temperature and pressure conditions.

A target payback period of five years was selected as an illustrative assessment criterion. The calculation used an initial investment of 1,197,390 UZS, 365 operating days per year, a methane volume fraction of 0.60, and lower heating values of 35.8 MJ/m³ for methane and 46.4 MJ/kg for LPG. Annual operating expenditure was initially set to zero. The assessment therefore represents a gross fuel-energy-equivalent scenario; actual savings depend additionally on operating expenditure and the relative efficiencies of biogas and LPG burners.

The LPG prices used in the two scenarios were:

$$p_{\mathrm{LPG,sub}} = \frac{43\,000}{20} = 2\,150\ \mathrm{UZS/kg},$$

$$p_{\mathrm{LPG,market}} = \frac{7\,000}{0.51} \approx 13\,725.5\ \mathrm{UZS/kg}.$$

Substituting these values into Eq. (9) gives the minimum daily biogas production required for a five-year simple payback:

$$V_{\mathrm{biogas,min,sub}} = \frac{1\,197\,390/5}{365\times0.60\times(35.8/46.4)\times2\,150} \approx 0.659\ \mathrm{m^3/day},$$

$$V_{\mathrm{biogas,min,market}} = \frac{1\,197\,390/5}{365 \times 0.60 \times (35.8/46.4) \times 13\,725.5} \approx 0.103\ \mathrm{m^3/day}.$$

Under the assumptions used in the payback calculation, the measured three-day mean of 0.220 m³/day exceeded the five-year payback threshold at the private-market LPG price (0.103 m³/day) but fell below the threshold at the subsidized LPG price (0.659 m³/day).

The initial investment was converted to local currency using the official exchange rate of 11,973.90 UZS per USD on 6 July 2026 [31]. The calculated payback periods and production thresholds are conditional on the assumed operating schedule, methane content, fuel prices, and operating expenditure. Annual savings were extrapolated from the reported daily production rather than measured over a full year. Filter replacement, maintenance, labour, and seasonal changes in gas production should therefore be included when assessing long-term financial performance. Digestate was excluded from the payback calculation because its fertilizer value and associated handling costs require separate assessment.

The key energy and economic performance indicators of the developed small-capacity biogas system are summarized in Table 5.

Table 5. Summary of energy and economic performance of the developed small-capacity biogas system

Parameter	Value
Average biogas production	0.22 ± 0.002 m³/day
Methane concentration	60.0 vol.%
Daily methane production	0.132 m³/day
Daily gross energy potential (MJ)	4.73 MJ/day
Daily gross energy potential (kWh)	1.31 kWh/day
Annual gross energy potential	479 kWh/year
LPG-equivalent displacement	3.05 kg/month
Annual LPG-equivalent displacement	37.2 kg/year
Equivalent 20-kg LPG cylinders	1.86 cylinders/year
Monthly household LPG-energy substitution	15.3%

Initial fabrication cost	≈ USD 100 (≈1,197,390 UZS)
Annual fuel saving (subsidized LPG scenario)	≈79,980 UZS/year (≈USD 6.7/year)
Annual fuel saving (private-market LPG scenario)	≈510,300 UZS/year (≈USD 42.6/year)
Simple payback period (fuel savings only) – subsidized scenario	≈ 15.0 years
Simple payback period (fuel savings only) – private-market scenario	≈ 2.35 years
Target simple payback period for threshold assessment	5 years
Minimum daily biogas production for five-year payback – subsidized LPG scenario	0.659 m^3/day
Minimum daily biogas production for five-year payback – private-market LPG scenario	0.103 m^3/day
Projected annual digestate volume (365 operating days)	≈ 1,642.5 L/year

The difference between the two payback scenarios arises from the price assigned to the displaced LPG, while digester investment and assumed gas production remain unchanged. The subsidized price reduces the monetary value of each unit of biogas produced, whereas the private-market price increases the potential fuel-cost saving. These scenarios therefore represent different household fuel-purchasing conditions. For households obtaining LPG from both sources, annual savings should be calculated using the respective quantities displaced at each price.

3.8. Practical Implications

The locally fabricated digester produced biogas from mixed agricultural residues under the tested operating conditions. The economic analysis shows that its potential to offset household cooking fuel costs depends on the price of the LPG it replaces. The digestate may offer an additional agricultural benefit, but its nutrient content and suitability for use as fertilizer require separate assessment [17].

The digester was evaluated at 35-37 °C. Repeated TS and VS analyses of feed samples collected on different feeding days would help quantify feed variability and refine the calculated organic loading rate. Longer trials should track daily biogas production and methane content across seasons to determine how much LPG the digester could replace over a year. Tests at different operating temperatures would help establish whether the production levels observed in this study can be sustained under cooler conditions. Repeated measurements of hydrogen sulfide at the inlet and outlet of the gas treatment unit would show how its performance changes over time. Measuring the nutrient content and characterizing the physicochemical properties of the digestate would help assess its suitability for agricultural use. These measurements would provide a basis for evaluating the system's long-term performance and refining the economic estimates.

4. Conclusion

This study presented the design, fabrication, and experimental evaluation of an ultra-low-cost household-scale biogas digester intended for decentralized rural applications. Following the initial batch phase, daily supplementary feeding began on 17 August 2026, and recorded biogas production ranged from 218 to 222 L/day during 18-25 August under mesophilic conditions.

Mean daily biogas production on 18-20 August 2026 was 0.220 ± 0.002 m^3/day (mean ± sample standard deviation; n = 3). The measured methane volume fraction was 60.0%, and substrate pH ranged from 6.8 to 7.3 across the three sampling occasions.

Energy calculations based on the reported daily biogas production and methane content indicated a gross energy potential of approximately 1.31 kWh/day. Assuming unchanged production over 365 operating days, this corresponds to approximately 479 kWh/year and a gross energy equivalent of 37.2 kg of LPG. At a reported fabrication cost of approximately USD 100, excluding the burner, the fuel-only simple payback period was approximately 2.35 years under private-market LPG prices and 15.0 years under subsidized prices. For an illustrative five-year payback target, the required daily biogas production was approximately 0.103 and 0.659 m^3/day, respectively. These estimates assume zero annual operating expenditure and gross fuel-energy equivalence. Digestate was excluded from the monetary benefit calculation.

The study documents biogas production from locally available agricultural residues in a manually mixed digester under the tested mesophilic conditions. The economic analysis identifies the daily biogas output required for a five-year payback under two LPG pricing scenarios in Uzbekistan. At the observed production level, this target was met in the private-market scenario under the stated assumptions. The agricultural value of the digestate remains to be determined.

Comparative trials are planned in Azerbaijan using a monitoring protocol comparable to that used in Uzbekistan. The trials will assess whether the observed biogas production can be reproduced under local operating conditions and how differences in gas output, operating costs, and LPG prices affect the estimated payback period.

CRediT authorship contribution statement

Muzaffar Khabibullaevich Murodov: Conceptualization, Methodology, Investigation, Writing - original draft, Project administration.

Vagif Hasanov: Supervision, Conceptualization, Writing - review & editing, Funding acquisition.

Ilnur Kh. Gayfullin: Formal analysis, Validation.

Samir Orujov: Writing - review & editing, Conceptualization,

Akhmedov Avazbek Bokhodir ogli: Investigation, Data curation, Visualization.
Ghadder Ghabour: Formal analysis, Software, Validation.
Mohamad Amir Hababa: Visualization, Resources, Writing - review & editing.

Declarations

Funding: The authors declare that no funds, grants, or other financial support were received during the preparation of this manuscript.

Competing interests: The authors have no relevant financial or non-financial interests to disclose.

Data availability: The datasets generated and/or analysed during the current study are available from the corresponding author on reasonable request.

Corresponding author: Correspondence to Samir Orujov (samir.orujov@sdu.edu.az).

References

1. Kothari, R., Tyagi, V. V., & Pathak, A. (2010). Waste-to-energy: A way from renewable energy sources to sustainable development. Renewable and Sustainable Energy Reviews, 14(9), 3164-3170. DOI: https://doi.org/10.1016/j.rser.2010.05.005
2. Angelidaki, I., Treu, L., Tsapekos, P., Luo, G., Campanaro, S., Wenzel, H., & Kougias, P. G. (2018). Biogas upgrading and utilization: Current status and perspectives. Biotechnology Advances, 36(2), 452-466. DOI: https://doi.org/10.1016/j.biotechadv.2018.01.011
3. Elsayed, A., Kakar, F. L., Abdelrahman, A. M., Ahmed, N., AlSayed, A., Zagloul, M. S., ... & Elbeshbishy, E. (2024). Enhancing anaerobic digestion efficiency: A comprehensive review on innovative intensification technologies. Energy Conversion and Management, 320, 118979. DOI: https://doi.org/10.1016/j.enconman.2024.118979
4. Scarlat, N., Dallemand, J. F., & Fahl, F. (2018). Biogas: Developments and perspectives in Europe. Renewable Energy, 129, 457-472. DOI: https://doi.org/10.1016/j.renene.2018.03.006
5. Ward, A. J., Hobbs, P. J., Holliman, P. J., & Jones, D. L. (2008). Optimisation of the anaerobic digestion of agricultural resources. Bioresource Technology, 99(17), 7928-7940. DOI: https://doi.org/10.1016/j.biortech.2008.02.044
6. Mata-Alvarez, J., Dosta, J., Romero-Güiza, M. S., Fonoll, X., Peces, M., & Astals, S. (2014). A critical review on anaerobic co-digestion achievements between 2010 and 2013. Renewable and Sustainable Energy Reviews, 36, 412-427. DOI: https://doi.org/10.1016/j.rser.2014.04.039
7. Mao, C., Feng, Y., Wang, X., & Ren, G. (2015). Review on research achievements of biogas from anaerobic digestion. Renewable and Sustainable Energy Reviews, 45, 540-555.DOI: https://doi.org/10.1016/j.rser.2015.02.032
8. Weiland, P. (2010). Biogas production: Current state and perspectives. Applied Microbiology and Biotechnology, 85(4), 849-860. DOI: https://doi.org/10.1007/s00253-009-2246-7
9. Appels, L., Baeyens, J., Degrève, J., & Dewil, R. (2008). Principles and potential of the anaerobic digestion of waste-activated sludge. Progress in Energy and Combustion Science, 34(6), 755-781.DOI: https://doi.org/10.1016/j.pecs.2008.06.002
10. Rajendran, K., Aslanzadeh, S., & Taherzadeh, M. J. (2012). Household Biogas Digesters – A Review. Energies, 5(8), 2911-2942. https://doi.org/10.3390/en5082911
11. Obileke, K. C., Onyeaka, H., Meyer, E. L., & Nwokolo, N. (2021). Materials for the design and construction of household biogas digesters for biogas production: A review. International Journal of Energy Research, 45(9), 13249-13271. DOI: https://doi.org/10.1002/er.6120
12. Cheng, S., Li, Z., Mang, H.-P., Huba, E.-M., Gao, R., & Wang, X. (2014). Development and application of prefabricated biogas digesters in developing countries. Renewable and Sustainable Energy Reviews, 34, 387-400. DOI: https://doi.org/10.1016/j.rser.2014.03.035
13. Hasanov V., Orujov S., İbrahimli E., Aliyeva G., Karimova S. (2026). Thermal improvement and corrosion resistance of glass- and enamel-coated heat-exchange tubes. 5(2026), 119-135. DOI: https://doi.org/10.21303/2461-4262.2026.004401
14. Singh, B., Szamosi, Z., & Siménfalvi, Z. (2019). State of the art on mixing in an anaerobic digester: A review. Renewable Energy, 141, 922-936. DOI: https://doi.org/10.1016/j.renene.2019.04.072
15. Ma, G., Ndegwa, P. M., Harrison, J. H., & Chen, Y. (2020). Methane yields during anaerobic co-digestion of animal manure with other feedstocks: A meta-analysis. Science of the Total Environment, 728, 138224. DOI: https://doi.org/10.1016/j.scitotenv.2020.138224
16. Chen, Y., Cheng, J. J., & Creamer, K. S. (2008). Inhibition of anaerobic digestion process: A review. Bioresource Technology, 99(10), 4044-4064. DOI: https://doi.org/10.1016/j.biortech.2007.01.057
17. Möller, K., & Müller, T. (2012). Effects of anaerobic digestion on digestate nutrient availability and crop growth: A review. Engineering in Life Sciences, 12(3), 242-257. DOI: https://doi.org/10.1002/elsc.201100085
18. Goux, X., Calusinska, M., Fossépré, M., Benizri, E., & Delfosse, P. (2016). Start-up phase of an anaerobic full-scale farm reactor – Appearance of mesophilic anaerobic conditions and establishment of the methanogenic microbial community. Bioresource Technology, 212, 217-226. DOI: https://doi.org/10.1016/j.biortech.2016.04.040
19. Abd Allah, W. E., Tawfik, M. A., Sagade, A., Gorjian, S., Metwally, K. A., & El-Shal, H. (2021). Methane production enhancement of a family-scale biogas digester using cattle manure and corn stover under cold climates. Sustainable Energy

Technologies and Assessments, 45, 101163. DOI: https://doi.org/10.1016/j.seta.2021.101163
20. Ahlberg-Eliasson, K., Westerholm, M., Isaksson, S., & Schnürer, A. (2021). Anaerobic Digestion of Animal Manure and Influence of Organic Loading Rate and Temperature on Process Performance, Microbiology, and Methane Emission From Digestates. Frontiers in Energy Research, 9, 740314. DOI: https://doi.org/10.3389/fenrg.2021.740314
21. Arias, D. E., Veluchamy, C., Habash, M. B., & Gilroyed, B. H. (2021). Biogas production, waste stabilization efficiency, and hygienization potential of a mesophilic anaerobic plug flow reactor processing swine manure and corn stover. Journal of Environmental Management, 284, 112027. DOI: https://doi.org/10.1016/j.jenvman.2021.112027
22. Lindmark, J., Thorin, E., Bel Fdhila, R., & Dahlquist, E. (2014). Effects of mixing on the result of anaerobic digestion: Review. Renewable and Sustainable Energy Reviews, 40, 1030-1047. DOI: https://doi.org/10.1016/j.rser.2014.07.182
23. Su, H., Liu, L., Wang, S., Wang, Q., Jiang, Y., Hou, X., & Tan, T. (2015). Semi-continuous anaerobic digestion for biogas production: Influence of ammonium acetate supplement and structure of the microbial community. Biotechnology for Biofuels, 8, 13. DOI: https://doi.org/10.1186/s13068-015-0197-z
24. Bharathiraja, B., Sudharsana, T., Jayamuthunagai, J., Praveenkumar, R., Chozhavendhan, S., & Iyyappan, J. (2018). Biogas production – A review on composition, fuel properties, feed stock and principles of anaerobic digestion. Renewable and Sustainable Energy Reviews, 90, 570-582. DOI: https://doi.org/10.1016/j.rser.2018.03.093
25. Ryckebosch, E., Drouillon, M., & Vervaeren, H. (2011). Techniques for transformation of biogas to biomethane. Biomass and Bioenergy, 35(5), 1633-1645. DOI: https://doi.org/10.1016/j.biombioe.2011.02.033
26. Sun, Q., Li, H., Yan, J., Liu, L., Yu, Z., & Yu, X. (2015). Selection of appropriate biogas upgrading technology — A review of biogas cleaning, upgrading and utilisation. Renewable and Sustainable Energy Reviews, 51, 521-532. DOI: https://doi.org/10.1016/j.rser.2015.06.029
27. Wang, S., Xu, C., Song, L., & Zhang, J. (2022). Anaerobic Digestion of Food Waste and Its Microbial Consortia: A Historical Review and Future Perspectives. *International Journal of Environmental Research and Public Health, 19*(15), 9519. https://doi.org/10.3390/ijerph19159519
28. Ihász, R., & Laza, T. (2017). Determining the biogas potential of agricultural by-products in a Hungarian subregion. WIREs Energy and Environment, 6(3), e219. DOI: https://doi.org/10.1002/wene.219
29. Weyant, C. L., Thompson, R., Lam, N. L., Upadhyay, B., Shrestha, P., Maharjan, S., Rai, K., Adhikari, C., Fox, M. C., & Pokhrel, A. K. (2019). In-Field Emission Measurements from Biogas and Liquified Petroleum Gas (LPG) Stoves. Atmosphere, 10(12), 729. https://doi.org/10.3390/atmos10120729
30. Issah, A.-A., Kabera, T., & Kemausuor, F. (2020). Biogas optimisation processes and effluent quality: A review. Biomass and Bioenergy, 133, 105449. https://doi.org/10.1016/j.biombioe.2019.105449
31. Central Bank of the Republic of Uzbekistan. Official exchange rate (6 July 2026). https://cbu.uz/en/arkhiv-kursov-valyut/