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ARTICLE

Economic and Technical Efficiency Aspects of Biogas Production for Farm Waste Processing: Case of Slovakia Agriculture

Peter Bielik [1], *Izabela Adamickova* [2*], *Erik Sandor* [1], *Stefaniia Belinska* [3], *Janina Belinska* [4]

[1] *Faculty of Economics and Entrepreneurship, Pan European University, Tomášikova 20, 821 02 Bratislava, Slovakia*

[2] *Faculty of Economics and Management, Slovak University of Agriculture in Nitra, Trieda Andreja Hlinku 2, 949 76 Nitra, Slovakia*

[3] *Grant Thornton Audit s.r.o., Hodžovo námestie 1/A, 811 06 Bratislava, Slovakia*

[4] *International Economic Relations Department, State Tax University, 31 Universytetska St, 08200 Irpin, Ukraine*

ABSTRACT

The article focuses on evaluating both the economic and technical efficiency of biogas plants that are designed to process agricultural waste and farm by-products. The primary aim is to provide a comprehensive assessment of economic performance, applied technological solutions, and different capacity configurations, while also examining their influence on biogas production efficiency and investment payback periods. The study compares various fermentation technologies, analyses the characteristics of input substrates, and explores optimization strategies aimed at maximizing energy output. Economic and technical efficiency is understood as the ability of a biogas plant to utilize available resources in the most effective way to produce energy and other outputs. To improve the allocation of agricultural land used for biomass production, the research applies the methodology of technical efficiency frontiers. This approach helps identify optimal production combinations. Furthermore, correlation and regression analysis are used to measure the relationship between farm income and selected variables, allowing the identification of the most influential factors affecting financial performance. Sensitivity analysis is also conducted to examine how key economic indicators, such as yields, Net Present Value (NPV), and Internal Rate of Return (IRR), respond

*CORRESPONDING AUTHOR:

Izabela Adamickova, Faculty of Economics and Management, Slovak University of Agriculture in Nitra, Trieda Andreja Hlinku 2, 949 76 Nitra, Slovakia; Email: izabela.adamickova@uniag.sk

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to changes in input parameters. The results emphasize the crucial determinants of profitability and highlight the role of biogas plants in supporting sustainable agricultural development.

Keywords: Biogas Plant; Agricultural Waste; Techno-Economic Analysis; Bioenergy; Sustainable Agriculture; Input and Output Prices; Operating Investment Costs; Bioeconomy

1. Introduction

The importance of renewable energy sources and sustainable resource management has become a key topic in modern agricultural and economic research. Economic and technical efficiency examines how effectively a biogas plant uses its resources to generate outputs [1]. The role of biomass as a promising source of sustainability for agricultural farms has been emphasized in the research and published works of many authors [2–6]. According to published findings, the development of the bioeconomy can help increase farmers' incomes and raise the standard of living in each country. On the one hand, higher demand for agricultural products can lead to price growth and consequently higher farm incomes [7]. The European Union estimates that global demand for food will increase by 70% by 2050, accompanied by a dramatic rise in the demand for biomass for industrial purposes [8].

The production of bioeconomy-related goods can also create new opportunities for value-added industries in both developed and developing countries [2]. As a result, new jobs may be generated outside the farm sector, while rising labour productivity and yields exert downward pressure on food prices. For example, every million liters of bioethanol produced generates around 38 jobs, meaning that biogas enterprises create employment not in the maintenance of "pipelines," but directly in agricultural regions. The primary raw materials for most bioeconomy products include sugar (glucose), starch (grain, sugarcane), and cellulose (straw, sawdust).

The bioeconomy contributes to the implementation of sustainable development principles by diversifying and expanding the agrarian economy, supporting rural development, improving social conditions in urban and rural areas, enhancing human health, ecology, and quality of life, reducing costs, strengthening quality control, creating new products and markets, and decreasing dependence on fossil fuels [9]. Increased biomass production can affect both income and the labour market, while greater farm productivity can influence income and the environment. At the same time, the use of marginal land may negatively affect local communities and biodiversity. These three aspects, therefore, complement one another, but each contributes to different Sustainable Development Goals [10].

The effectiveness of the bioeconomy in addressing many of the pressing challenges of the modern economy has been confirmed by numerous studies [11]. According to these authors, the sustainable bioeconomy should be based on improved efficiency in the use of resources and biomass. The application of multipurpose raw materials is particularly advantageous in adding value to biomass, as it enables the production of multiple bioproducts.

Agriculture provides raw materials for liquid fuels and value-added products (chemicals and materials), as well as healthy and safe food, which enhances the sector's ability to generate additional income [12]. Currently, the dominant global trend is the use of biomass to replace expensive natural gas and to reduce carbon emissions, a trend that is gaining increasing momentum. The scientific basis for this development was established by Swedish researchers [13], who demonstrated that increased biomass utilization contributes to a reduction in CO_2 emissions and overall fuel consumption for various purposes, in line with national strategic objectives.

Scientists assess the potential of agriculture to supply raw materials for liquid fuels and value-added products (chemicals and materials), as well as healthy and safe food and feed, as very high [12].

According to a Joint Research Centre (JRC) study on the development and prospects of biogas in Europe [14]. Slovakia produces approximately 6,223 TJ of biogas, corresponding to 173 million cubic metres. Total natural gas consumption in Slovakia amounts to 4,512 million cubic metres, meaning that biogas currently substitutes approximately 3.8% of natural gas consumption. Anaerobic digestion (including manure processing) is the dominant method of biogas production in Slovakia, accounting for around 85% of total biogas output.

The use of biomass as an industrial raw material has a positive impact on the production of food and other biomaterials, leading to an increased contribution of agriculture to gross domestic product [2]. Moreover, rural areas are becoming an increasingly important source of renewable energy—including hydropower, wind, solar, geothermal energy, and biomass—and thus play a key role in the decentralisation of energy transformation and form the foundation for the future energy sector. Consequently, biomass utilisation can significantly enhance energy security in rural areas [2].

For agricultural enterprises, the use of biomass for energy purposes enables:

- covering their own energy needs through renewable energy sources, which, under conditions of high energy intensity and rising fossil fuel prices, enhances competitiveness;
- reducing greenhouse gas emissions from manure management;
- increasing revenues through the sale of complementary by-products.

The energy utilisation of plant residues is also feasible. According to the results of approximately a dozen studies, 25–50% of straw and nutrient residues from grain maize production and 30–50% of residues from sunflower production can be used for energy purposes, while the remaining biomass should be left in the fields to maintain soil quality. Studies conducted in the United States indicate that 30–60% of total straw and maize residues can be used for energy or biofuel production through appropriate tillage technologies [5].

Biomass can replace fossil fuels in several sectors with varying levels of energy efficiency. It can be directly combusted to generate heat or electricity. In cogeneration plants, biomass can simultaneously produce heat and power, ensuring more efficient use of its energy potential. Alternatively, biofuels can be produced through thermochemical processes (pyrolysis, gasification) or biochemical processes (alcoholic and methane fermentation), which are particularly important for the transport sector [5].

A study conducted in Slovakia focused on residual biomass and found that in 2019 the total production of usable post-harvest residues from selected crops amounted to approximately 4.85 million tons. The estimated energy potential of this biomass was 68 PJ (petajoules). Among these residues, the highest energy potential was provided by maize (21.8 PJ), wheat (19.4 PJ), and permanent grasslands (10.9 PJ). The study also highlights differences between territorial regions, which influence the overall production potential of biomass [3].

2. Materials and Methods

The main aim of the article is to provide a comprehensive evaluation of the economic aspects and technical efficiency of biogas plants (BPS) in relation to the production and processing of agricultural waste, and to highlight the key factors determining their efficiency, profitability, and contribution to sustainable agriculture. The specific objectives are to generalize global experiences in biofuel production to determine the possibilities and limitations of biogas production in Slovakia, and to evaluate the efficiency of selecting specific biogas plants for processing farm-derived biological inputs.

The methodology establishes a framework for assessing both the technical parameters of biogas plants and their economic performance in agricultural waste processing. The evaluation is based on a combination of secondary data analysis and computational models of economic profitability.

The analysis draws on the following sources:

- Technical documentation and operational data of BPS;
- Case studies of model farms operating BPS of different sizes (small < 100 kW, medium 100–500 kW, large > 500 kW).

To evaluate the technical parameters of BPS, a questionnaire survey was conducted to identify:

- Type of technology (continuous/discontinuous, mesophilic/thermophilic);

- Installed electrical capacity (kW);
- Daily substrate volume (m^3) and its composition;
- Dry matter content (%) and organic dry matter (%);
- Biogas yield (m^3/t substrate);
- Energy efficiency of the cogeneration unit (% for electricity and heat).

For the assessment of economic efficiency, the following indicators were monitored:

- Investment costs (CAPEX)—including technology, construction works, and connections;
- Operating costs (OPEX)—covering maintenance, operation, energy, and substrate transport;
- Revenues from electricity and heat sales (€/MWh);
- Revenues from by-products (digestate);
- Internal Rate of Return (IRR) – discount rate at which Net Present Value (NPV) = 0;
- Payback Period – time required to recover the investment.

To examine the influence of external factors, a sensitivity analysis was carried out on key input variables:

- Changes in electricity prices (±20%);
- Variations in input costs;
- Investment costs and interest rates;
- Changes in substrate volume and biogas yield.

Sensitivity analysis explores how the outcome (e.g., revenues, NPV, IRR) varies when key input parameters change [15]. Its calculation and interpretation are as follows:

$$S = \frac{\%change\ in\ output}{\%change\ in\ input}$$

- **S > 1** → the output is highly sensitive to changes in the input (risk factor);
- **S = 1** → proportional change;
- **S < 1** → low sensitivity parameter.

To optimize the allocation of crop areas intended for biomass production, the method of configuring technical efficiency lines is applied to graphically express the Production Possibility Frontier (PPF) [16]. The principle of this optimization is to shift the positions toward the origin, i.e., the X and Y axes. The procedure is based on optimizing the allocation of agricultural crop areas according to the ratio between the bioethanol yield per ton of raw material and the bioethanol yield per hectare of land, relative to the crop yields from which bioethanol is produced.

The model may generate the following dependencies:

a) The extreme positions of crops with inefficient bioethanol production relate to the origin coordinates: 0–1 (sugar beet) and 0–5 (barley).
b) A perpendicular is drawn from the position of crop 4 (wheat), which represents efficient bioethanol production, to the Y-axis.
c) The intersection points of the perpendicular with segments 0–1 and 0–5 are marked as 11 and 51(41), respectively.
d) A new line of technical efficiency, 11–51(41), is created.

This results in new positions representing the ratio between the bioethanol output per ton of raw material and crop yield, as well as the ratio between the bioethanol output per hectare of land and crop fertility.

Following the method by Brown [17], the efficiency of a biogas unit in utilizing its resources to produce outputs can be evaluated. Input and output sets are expressed as:

$$X = (x_1, x_2, \ldots, x_n), Y = (y_1, y_2, \ldots, y_m).$$

Correlation–regression analysis (Karl Pearson) was employed to quantify the dependence of farm income on specific factors and to identify the most significant indicators influencing the variable. A general multiple regression model is expressed as:

$$Y = b_0 + b_1 X_1 + b_2 X_2 + \cdots + b_n X_n + \varepsilon.$$

Where:

- Y—dependent variable;
- b_0—intercept;
- b_n – regression coefficient;
- X_n—factor (independent variable);
- ε—random error term.

A correlation matrix was calculated to measure the strength of linear relationships between different pairs of variables, considering that each pairwise relationship may be influenced by links with other variables.

A mixed-method research (MMR) approach was used to determine the motives and objectives behind the decision to produce biofuels. This method was based on a questionnaire and the statistical processing of the results using correlation analysis, as well as content analysis. To validate the questionnaire using the obtained data, the Cronbach's Alpha internal consistency test, Exploratory Factor Analysis (EFA), and Confirmatory Factor Analysis (CFA) were employed [18, 19].

To verify the effectiveness of the proposed questionnaire for determining the potential of biofuel production and utilization on agricultural farms, an Exploratory Factor Analysis (EFA) was conducted [5]. The factor analysis was performed using varimax rotation and principal axis factoring (**Table 1**). Elements with a factor loading below 0.5 were excluded; in this study, all factors had loadings above 0.5.

Table 1. Cronbach's Alpha Test Results.

Conceptual Part	Number of Items	Cronbach's Alpha
Potential for biofuel production and use	24	0.80
Awareness in the field of biofuel production and use	9	0.75
Readiness of the enterprise's production base for biofuel production	4	0.83
Readiness of the administrative apparatus for biofuel production	4	0.78
Status of biofuel production implementation	4	0.84
Social responsibility	3	0.76
Energy autonomy of the agricultural enterprise	6	0.73

Source: own processing.

The validation of the questionnaire in this study was based on Confirmatory Factor Analysis (CFA). This approach was implemented following Preiser et al. [20] with established applications in similar studies [21].

To verify the proposed model using the maximum likelihood method, a second-order confirmatory factor model was applied (**Tables 2** and **3**). CFA is based on comparing the variance–covariance matrix obtained from the sample with the one generated by the model (**Table 2**).

Table 2. Model Results.

Model	X^2	df	*p*-Value	Cmin/df	RMSEA	CFI	P/Rating
EA	315.852	72.3	0.0001	4.368	0.057	0.905	(0.62–0.97)

Note: All factor loadings were statistically significant at $\alpha = 0.05$.
Source: own processing.

Table 3. Final Statistical Indices for the Overall Model Structure.

Model	X^2	df	*p*-Value	Cmin/df	RMSEA	CFI	P/Rating
EA—Energy autonomy	562.34	148.82	0.001	3.778	0.0602	0.916	(0.60–0.90)

Source: own processing.

The results in **Table 3** confirm the adequacy of the model. The chi-square norm (Cmin/df) is below 5, RMSEA < 0.08, and CFI > 0.9, which are considered acceptable thresholds [22].

All model parameters were statistically significant and practically meaningful. Factor loadings ranged from 0.60 to 0.90, exceeding the recommended threshold of 0.5 [16]. The relationships between the two main variables were also significant (Cmin/df > 1.96). Overall, all indices confirm that the model demonstrates the presence of both direct and indirect relationships.

3. Results

In farm production conditions, a significant amount of organic waste is generated—slurry, manure, feed residues, and by-products of crop production. Inefficient processing of this waste can result in environmental burdens, increased greenhouse gas emissions, and hygiene risks. One promising solution is the use of biogas plants (BPS), which enable the energy recovery of these materials through anaerobic fermentation, leading to the production of biogas and, subsequently, electricity and heat.

The economic efficiency of BPS, however, is determined by several factors. At the technical level, it depends on the appropriate choice of fermentation technology, plant capacity, quality of input substrates, and the optimization of operational parameters (temperature, retention time, mixing). From an economic perspective, the decisive factors include investment costs, operating expenses, availability of subsidies, revenues from energy sales, and the utilization of by-products (such as digestate used as fertilizer). An equally important aspect is the legislative framework and its influence on the operation and profitability of BPS in the Slovak Republic.

In Slovakia, support for BPS is provided through Act No. 309/2009 Coll. on the Support of Renewable Energy Sources (RES), as well as state aid schemes and subsidy programs offered by the Ministry of Agriculture of the Slovak Republic.

3.1. Technical Aspects of Biogas Plant Operation

Biogas plants designed to process farm waste differ primarily in size, type of technology and composition of substrates. Three model variants were defined for the analysis (**Table 4**).

3.2. Economic Aspects of the Acquisition and Operation of Biogas Plants

For the economic analysis, indicative investment and operating costs, revenues and efficiency indicators were calculated for three model sizes of BPS (**Table 5**). The discount rate was chosen as 6%, and the project life was 15 years.

Table 4. Technical aspects of biogas plant operation.

Parameter	Small BPS	Medium BPS	Large BPS
Electrical output (kW)	75	300	750
Annual electricity production (MWh)	600	2,400	6,000
Substrate consumption (t/year)	2,500	10,000	25,000
Substrate type	Manure, silage	Manure, silage, feed residues	Manure, silage, plant by-products
Fermentation process	Mesophilic (38 °C)	Mesophilic	Mesophilic / Thermophilic
Biogas yield (m^3/t)	110	115	120

Source: own processing, questionnaire survey.

Table 5. Economic aspects of the acquisition and operation of biogas plants.

Indicator	Small BPS (75 kW)	Medium BPS (300 kW)	Large BPS (750 kW)
Investment costs (EUR)	750,000	2,400,000	5,000,000
Operating costs/year (EUR)	70,000	200,000	400,000
Revenue from electricity sales/year (EUR)	90,000	360,000	900,000
Revenue from heat and digestate (EUR)	10,000	50,000	120,000
Net annual cash flow (EUR)	30,000	210,000	620,000
NPV (at 6%)	−100,000	+400,000	+1,500,000
IRR	4%	8%	11%
Payback period (years)	>15	11	8

Source: questionnaire survey, processed according to Koval et al. [15], and Statistical Office of the Slovak Republic [23].

The results show that BPS with an output of 75 kW are economically problematic without subsidies or their own heat consumption, as they are at the limit of profitability. Medium-sized BPS are economically viable at current energy prices, especially if they use heat and receive support from the RDP or a guaranteed feed-in tariff. Large BPS (750 kW) achieves the best results due to economies of scale and better use of cogeneration.

Biogas plants with a capacity of up to 500 kW are generally designed for medium-sized and large integrated agricultural enterprises that combine animal husbandry and crop production. Such facilities aim to cover a substantial share of their energy demand using on-farm resources while simultaneously producing thermal energy for purposes such as heating livestock buildings and drying agricultural products.

Biogas plants with an installed capacity of up to 1 MW are suitable for large agricultural companies or enterprises that consider energy production as a distinct profit centre. These plants are particularly appropriate for farms managing several thousand hectares of land and operating large-scale, industrial livestock production systems.

The categorisation of biogas plants is addressed by several international institutions, such as the IEA (International Energy Agency), IRENA (International Renewable Energy Agency), and the EBA (European Biogas Association). Their annual reports provide statistical breakdowns of installed biogas plant capacity across Europe and analyse global market dynamics and economies of scale. These factors directly influence which biogas plant sizes are politically supported and economically preferred (**Table 6**).

Table 6. Technical data and characteristics of biogas plants.

Model	Biogas Plant-20	Biogas Plant-30	Biogas Plant-50	Biogas Plant-100
Bioreactor volume (m^3)	20	30	50	100
Daily loading of fresh manure, wet weight 75% (kg)	308	462	770	1,540
Daily loading of diluted manure, moisture 94% (kg)	966	1,449	2,415	4,830
Daily biogas yield/natural gas equivalent (m^3)	18.62/12	27.93/18	46.55/30	93.1/60
Annual production of biofertiliser, moisture 95%/nitroammophoska equivalent (t)	350/1.12	511/1.68	876/2.8	1,700/5.6
Fertilised area (ha)	3.2	4.8	8	16
Built-up area (m)	5 × 20	10 × 15	10 × 30	15 × 40

Source: questionnaire survey, processed according to Koval et al. [15] and Statistical Office of the Slovak Republic [23].

From the results of the sensitivity analysis [24], we can draw the following conclusions (**Figure 1**):

- A decrease in the electricity feed-in tariff by 20% will extend the payback by 2–3 years and may reduce the IRR below an acceptable level for SaM (small and medium-sized BPS).
- An increase in investment costs by 10% will reduce the NPV by approximately 12%.
- An increase in biogas yield by 10% will improve the IRR by 1–2 percentage points.

The tornado diagram shows that annual revenues have the largest positive impact on NPV, while costs (investment, operating, biomass price) have a negative, but equally strong effect.

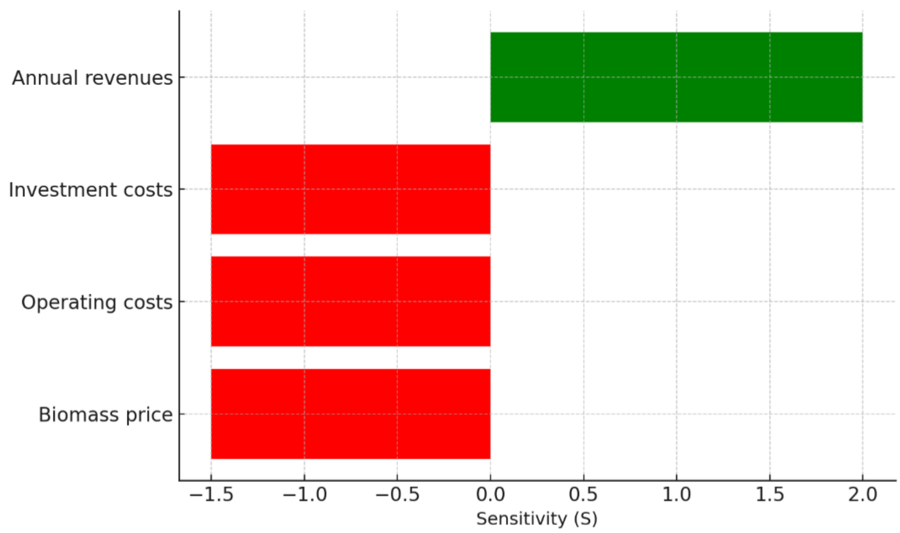

Figure 1. Sensitivity table (S) and tornado diagram.

Source: own calculations according to Hesse-Biber [19].

Results achieved and their interpretation:

- **Annual revenues (S = 2.0):** NPV is most sensitive to changes in revenues (e.g., electricity prices or heat sales). An increase in revenues by 10% will improve NPV by approximately 20%.
- **Investment costs, Operating costs, Biomass price (S = −1.5):** An increase in these items by 10% will reduce NPV by approximately 15%. All cost items have a negative impact.

Slovakia and Its Position in the Production of Bioethanol and Biodiesel

In most European countries, biogas plants with a capacity of less than 80 kW (usually up to and including 75 kW) are considered low power. Such small biogas plants will be in demand if they are relatively inexpensive and offer a quick return on investment. A low-capacity biogas plant operates with organic waste volumes of around 10 kg per day, waste from 100–200 cows, or 200–5000 t of organic waste per year. This variability depends on the availability of waste and residues, which makes such solutions particularly suitable for SaM farms.

In Slovakia, fuel in the form of dendromass is also obtained from wood, from waste from the wood processing industry, and from raw materials derived from energy crops or other unused areas.

In some European countries, especially in Scandinavia, Poland, and Denmark, effective substitutes for forest-based solid biomass have been developed – energy crops: woody plants (willow, poplar, paulownia, etc.) and herbaceous plants (miscanthus, reed canary grass, etc.) [25].

Currently, about 64% of global bioethanol production comes from corn, 26% from sugarcane, 3% from molasses, 3% from wheat, and the remainder from other raw materials such as cassava or sugar beet.

The energetic use of crop residues is also feasible. According to relevant studies, 25–50% of straw yields and corn nutrient residues can be used for energy purposes, 30–50% of sunflower by-products, while the rest of the biomass should remain in the soil [26]. Studies conducted in the USA demonstrated that 30–60% of the total straw and corn residues could be used for energy/biofuel production through tillage technology [27].

The largest source of biowaste in Slovakia currently comes from crops (rye, barley, oats, corn, potatoes, rapeseed, and sugar beet), mostly as a by-product in the form of straw. Corn had the highest energy potential (28.1 PJ), followed by wheat (19 PJ) and sugar beet (14.2 PJ). These three crops also provided the highest theoretical amount of post-harvest residues. The total estimated usable residues amounted to 68 PJ, which corresponds to about 10% of Slovakia's total energy consumption.

For the efficiency calculation, we determined the approximate land area required for power plants and the crop types needed for the most efficient use of plant raw materials in biogas production in Slovakia. Using the method of functional environment analysis [1], calculations were performed to estimate crop yields and the potential bioethanol output from bioproducts (**Table 7**).

Table 7. Estimated yield of various agricultural crops and possible bioethanol yield from bioproducts.

Crop (Biofeedstock)	Planned Yield (t/ha)	Ethanol Output per Ton (l/t)	Ethanol Output per Hectare (l/ha)
Sugar beet	500	100	5,000
Jerusalem artichoke	300	87	2,610
Corn (grain)	70	416	2,912
Wheat	50	395	1,975
Barley	58	370	2,150
Sugarcane	650	70	4,550
Cassava	120	180	2,160

Source: own processing based on Kaletsnik et al. [9].

The obtained results indicate that the estimated level of production intensity exceeds the bioethanol yield per 1 t of sugar beet, Jerusalem artichoke, and sugarcane (**Table 8**).

The technical efficiency of bioethanol production by crop type (**Table 9**) highlights the differences that exist among individual crops grown under Slovak conditions. The most efficient crop is Jerusalem artichoke (0.88). Our research suggests that Jerusalem artichoke could be considered a suitable crop for future bioethanol production, although it is not as widely cultivated as maize. The reason is that Jerusalem artichoke tubers contain a high concentration of inulin, which, after hydrolysis, is converted into fructose that can be fermented into ethanol. While Jerusalem artichoke offers advantages such as the possibility of cultivation on less fertile soils, its commercial use in Slovakia is still limited compared to traditional crops.

Table 8. Crop ratio between bioethanol yield and land productivity.

No.	Crop	X1/Y (Ethanol from 1 t of Raw Material)	X2/Y (Ethanol from 1 ha of Land)
1	Sugar beet	0.20	10.00
2	Jerusalem artichoke	0.29	8.70
3	Corn (grain)	5.94	41.60
4	Wheat	7.90	39.50
5	Barley	6.38	37.07
6	Sugarcane	0.11	7.00
7	Cassava	1.50	18.00

Source: author's own calculations.

Table 9. Calculation of the technical efficiency of bioethanol yield by crop type.

No.	Crop	Technical Efficiency Coefficient
1	Sugar beet	0.68
2	Jerusalem artichoke	0.88
3	Corn (grain)	0.38
4	Wheat	1.00
5	Barley	0.63
6	Sugarcane	1.00
7	Cassava	0.55

Source: author's own calculations.

To optimize the allocation of grain areas in the operational environment, we analyse the configuration of technical efficiency lines. The principle of this optimization is to direct these positions toward the origin, i.e., towards the X and Y axes (**Figure 2**).

Based on the characteristics of the operational environment, the highest efficiency indicators—achieved through optimal yields and greater bioethanol production per ton of raw material and per hectare—were observed for sugarcane and wheat. However, sugarcane cannot be grown under Slovakia's climate, leaving wheat, maize, and sugar beet as the most suitable crops for bioethanol production.

In terms of bioethanol, improving production efficiency is relatively easier, as the ratio coefficients for this fuel are closer to the coordinate axes. Nevertheless, given the current relationship between energy carrier prices and raw material costs, biofuel production is not yet economically sustainable. For example, the cost of producing maize silage has increased to €40 per ton, compared with €25 per ton in 2010, approaching the threshold for economic feasibility.

Potential strategies to address this include boosting crop yields through intensive farming practices, employing high-yield varieties and hybrids, and developing cultivation, post-harvest, and storage technologies tailored to regional conditions. Additionally, increasing the efficiency of crop processing is a crucial factor in improving overall bioethanol production viability.

To identify the relationship between the use of information sources on biofuels by managers of agricultural enterprises and their level of awareness regarding biofuel production and use, a correlation analysis was conducted. The analysis was based on a paired regression equation using a graphical method, and the results are presented in **Table 10** [18].

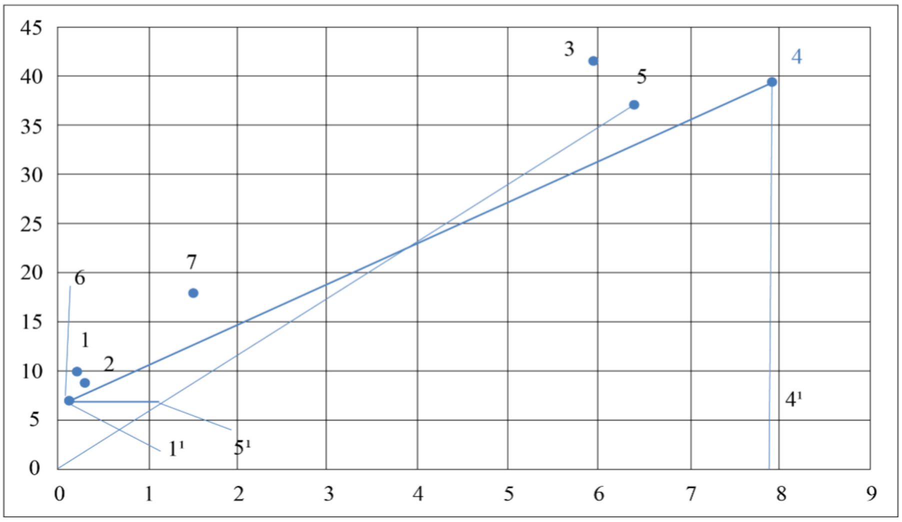

Figure 2. Optimizing the crop area by considering the ratio of bioethanol produced per ton of raw material to the total yield, and the ratio of bioethanol produced per hectare of land to the overall crop yield.

Source: author's own calculations according to Creswell and Plano-Clark [18].

Table 10. Results of paired regression analysis between biofuel awareness indicators and the selection of biofuel information sources.

Biofuel Awareness Indicator	Correlation Coefficient	Elasticity Coefficient	Strength of Correlation	Direction of Relationship
Knowledge of current legislation	0.386	0.283	Weak	Direct positive
Awareness of preferential feed-in tariffs	0.555	0.385	Moderately strong	Direct positive
Awareness of reduced excise tax rates on diesel or petrol	0.357	0.263	Weak	Direct positive
Knowledge of tax regulation mechanisms	0.342	0.247	Weak	Direct positive
Knowledge of types of biofuels and their benefits	0.357	0.263	Weak	Direct positive
Awareness of biofuel production options for agricultural enterprises	0.482	0.353	Moderately weak	Direct positive
Awareness of biofuel production from agricultural waste	0.482	0.353	Moderately weak	Direct positive
Awareness of grant opportunities for renewable energy projects	0.640	0.424	Moderately strong	Direct positive

Source: author's own calculations according to Creswell and Plano-Clark [18].

The data presented in **Table 10** indicate the existence of a direct relationship between the sources of information and the level of knowledge regarding biofuel production and use in the surveyed agricultural enterprises. A particularly notable correlation is observed between awareness of preferential feed-in tariffs and knowledge of grant opportunities for renewable energy projects, both of which are strongly linked to the sources of biofuel-related information [18].

It can be concluded that most representatives of the surveyed agricultural enterprises acquired knowledge of preferential tariffs and grant schemes during their university studies. Other types of knowledge are obtained in a more informal and unsystematic manner, primarily through communication with colleagues, mass media, and specialised online platforms [18].

According to the survey results, 87.5% of the surveyed farms use cereal straw for ploughing, 25% use it as bedding material, 12.5% for baling, and 12.5% for the production of briquettes and pellets.

To examine the attitudes of Slovak farmers towards biogas production, we conducted a survey of agricultural enterprises in Slovakia. The survey was carried out using an electronic form on the Survio platform, which was distributed via a direct link sent to the email addresses of agricultural enterprises. This method allowed us to collect data from a diverse group of representatives from agricultural enterprises of various sizes and forms of ownership.

The survey lasted three months, from September to November 2022. In total, 34 enterprises participated. The questionnaire was visited 75 times, with an overall completion rate of 45.3%. Of the respondents, 75% spent between 10 and 30 min completing the questionnaire.

The questionnaire used in this study contained two main variables, measured using specific scales: (1) the potential for biofuel production and use, and (2) the level of energy autonomy of an agricultural enterprise. The potential for biofuel production and use was assessed using five criteria, each addressed with specific questions. For example: "Does your enterprise produce crop waste?" "Does your enterprise generate animal by-products?" "Do you own intellectual property rights for biofuel production?" "Does your enterprise have free funds that can be invested in innovation?" and "Are innovation functions integrated into the organizational structure of your enterprise?"

The energy autonomy of agricultural enterprises was measured using six criteria with corresponding questions. For example: "A relatively small share of fuel and lubricants, electricity, and natural gas in your enterprise's production costs." Responses were collected using a five-point Likert scale, where '5' meant "strongly agree" and '1' meant "strongly disagree."

Survey data on the use of agricultural waste show that 62.5% of managers at the surveyed enterprises are aware of the advantages of various types of biofuels, and 75% are aware of the possibilities for their production. Furthermore, the results indicate that 87.5% of company directors are familiar with Slovak and EU legislation in the field of biofuels and biotechnology. However, only 62.5% are aware of biofuel quotas and targets for minimum biofuel content, as well as reduced excise duties on diesel fuel and gasoline, provided they contain the required minimum share of biofuel. Additionally, only 50% of managers are aware of measures supporting renewable energy sources for high-efficiency cogeneration (Law No. 309/2009), and just 25% are aware of grants available for renewable energy projects [18].

To explore the relationship between farm managers' willingness to invest in innovation and their readiness to produce and utilize biofuels, we conducted a correlation analysis based on a paired regression equation, the results of which are presented in **Table 11** [18].

To further examine the relationship between the presence of an innovation department in farms and their readiness for biofuel production and use, we conducted an additional correlation analysis based on a paired regression equation (**Table 12**).

Table 11. Results of paired regression of farms' readiness for biofuel production and use and readiness to invest in innovations.

Indicator of Biofuel Production and Use Potential	Correlation Coefficient	Elasticity Coefficient	Strength of Correlation	Direction of Relationship
Willingness to invest in biofuel production	0.68	0.742	Medium	Direct positive
Willingness to cooperate with state institutions in scientific and research support for biofuel production	0.235	0.188	Weak	Direct positive
Willingness to conclude business contracts with research institutes and/or higher education institutions	0.531	0.487	Medium	Direct positive
Willingness to conclude licensing agreements with research institutes and/or higher education institutions	0.369	0.320	Weak	Direct positive
Willingness to invest in improving the qualifications of workers in the field of bioenergy	0.508	0.508	Medium	Direct positive

Source: author's own calculations according to Creswell and Plano-Clark [18].

Table 12. Results of paired regression of indicators of farmers' readiness for biofuel production and use and the presence of an innovation department.

Indicator of Biofuel Production and Use Potential	Correlation Coefficient	Elasticity Coefficient	Strength of Correlation	Direction of Relationship
Willingness to invest in biofuel production	0.858	0.890	High	Direct positive
Willingness to cooperate with state institutions in scientific and research support for biofuel production	0.792	0.603	High	Direct positive
Willingness to conclude business contracts with research institutes and/or higher education institutions	0.691	0.603	Medium	Direct positive
Willingness to conclude licensing agreements with research institutes and/or higher education institutions	0.881	0.725	High	Direct positive
Willingness to invest in improving the qualifications of workers in the field of bioenergy	0.608	0.578	Medium	Direct positive

Source: author's own calculations according to Creswell and Plano-Clark [18].

4. Discussion

The analysis of the technical and economic aspects of biogas plants (BPS) in Slovakia shows that they represent an effective way of utilizing agricultural waste; however, their implementation is conditioned by several factors.

The implementation of biogas plants in rural areas offers clear benefits, as demonstrated by their successful use in countries with developed agricultural sectors. Biogas technologies contribute to renewable energy production, improved waste management, and reduced dependence on fossil fuels.

Analyses indicate that Slovak agriculture has sufficient biomass and agricultural residue potential to support biofuel production. The identified biogas capacity could replace a significant share of natural gas consumption, potentially covering up to one third of national demand.

Economic evaluations show that small-scale biogas plants can meet basic on-farm energy needs, particularly electricity and heating. However, profitability may fluctuate over time, making financial support mechanisms and cost-reduction measures important for ensuring long-term economic viability.

From a technological perspective, agricultural residues such as manure, silage, and crop by-products are suitable substrates for anaerobic fermentation. A significant advantage is the environmental benefit in the form of reducing greenhouse gas emissions and producing organic fertilizer (digestate) [9]. Nevertheless, the stability of the fermentation process remains a challenge in smaller plants, where substrate diversification is limited.

From an economic perspective, the main constraint is the high capital intensity of such projects. Biogas plants are highly sensitive to energy prices, as confirmed by the sensitivity analysis: a 10% increase in revenues improves the net present value (NPV) by 20%, while a 10% increase in investment or operating costs reduces the NPV by 15%. Operating costs are primarily determined by substrate and logistics expenses [28].

Without state support or subsidy mechanisms, the payback period often extends beyond 12 years, which may be unacceptable for farmers. The total costs of a biogas plant vary depending on its size, location, and technological model. In addition to the high initial investment, limited access to favourable credit conditions further hinders the construction of biogas reactors. The absence of state subsidies to support biogas plants represents another barrier to their wider adoption in Slovakia.

5. Conclusions

Based on the results achieved, the following economic and technical barriers to the development of biogas plants (BPS) in Slovakia have been identified:

- High investment costs for establishing biogas plants.
- Fluctuations in energy prices.
- One-sided substrate composition.
- Limited willingness to cooperate with state institutions in scientific and research support for biofuel production.
- Limited willingness to conclude licensing agreements with research institutes.
- Shortage of qualified personnel.
- Complex approval procedures and high administrative burden.

In response to these identified barriers, the following measures are recommended:

A. Technical measures

- Introduction of automated control systems (e.g., pH, temperature, methane content sensors) to optimize the fermentation process.
- Implementation of co-fermentation using diverse substrates, which reduces the risk of process failure and increases overall biogas yield.
- Development of hybrid solutions (BPS combined with photovoltaics and heat storage) to enhance overall energy efficiency.

B. Economic measures

- Provision of preferential loans and grants for SaM farms planning to build BPS.
- Establishment of a long-term stable feed-in tariff system for electricity and heat generated from biogas (10–15 years).
- Support for the development of a market for digestate as a certified fertilizer, creating an additional income stream.

C. Organizational and legislative measures

- Encouragement of cooperation among smaller farms in constructing joint BPS facilities, thereby optimizing investment costs.
- Introduction of training and educational programs

for BPS operators, with a focus on ensuring technological stability and economic efficiency.

- Simplification of permitting procedures and establishment of clear legislative frameworks for the management of agricultural waste.

Author Contributions

Conceptualization: P.B. and S.B.; Methodology: P.B. and S.B.; Validation: I.A. and J.B.; Formal analysis: I.A.; Investigation: E.S.; Resources: I.A. and E.S.; Data curation, writing—original draft preparation: P.B. and S.B.; Writing—review and editing: P.B. and I.A.; Visualization: E.S.; Supervision: P.B. and I.A.; Project administration: I.A.; Funding acquisition: E.S. All authors have read and agreed to the published version of the manuscript.

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Data were obtained from the company owning the biogas plant that wants to remain anonymous and are available from the author Stefaniia Belinska with the permission of the company.

Conflicts of Interest

Author Belinska Stefaniia, as a former doctoral student was employed by Grant Thornton Audit, s.r.o. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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