



## Analysis of a Laboratory-Scale Biogas Plant's Performance in Single-Load Operation

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**Abstract:** The European policy for a carbon-neutral economy has led to a continuous increase in the demand for renewable energy sources (RES) within the energy mix of individual countries. Techniques and technologies for the conversion and utilization of various forms of "green" energy continue to evolve. One promising potential source of energy is the waste biomass from livestock and agriculture.

The examined scientific literature reveals a significant number of publications addressing various aspects of the biomass utilization process - from new designs of laboratory biogas installations to the impact of different factors on the methanogenesis process and biogas production.

This research introduces a newly designed laboratory research apparatus for a bioreactor aimed at a biogas production, offering the capability to regulate and investigate the influence of various parameters on the performance of the biogas installation. The apparatus's construction is described along with its capabilities for conducting scientific experiments.

A pilot was conducted to validate the functionality of the created laboratory research apparatus and the obtained results were analyzed. Conclusions and recommendations for future experiments are provided.

**Keywords:** RES, biogas technologies, animal biomass, anaerobic fermentation, energy balance

## Introduction

European policy for a carbon-neutral economy [8] is driving a continuous increase in the demand for quantities of renewable energy sources (RES) within the overall energy mix of individual countries. The revised Directive EU/2023/2413 [2] establishes a collective target for renewable energy of at least 42.5 % binding at the EU level by 2030 within an aspiration to reach 45 %. Significant attention and funding are devoted to the development of new technologies for harnessing a range of RES. The clear advantage lies with solar and wind energy which currently represent the largest share of utilized RES in contrast to the biomass.

However, the European Parliament anticipates an increase in biomethane production to 35 billion cubic meters by 2030 in accordance with the adopted REPowerEU Plan [7]. The advantage of this type of energy is its potential to reduce waste deposition, improve energy efficiency in wastewater treatment and supply renewable gas for various needs such as transportation, heating and production.

Food waste and wastewater can be utilized for renewable energy production, supporting local bioeconomies in Europe. Waste from livestock and biomass is converted into energy with residues serving as organic fertilizer, creating new business opportunities in agriculture. Biomethane not only helps reduce emissions in various sectors such as building, industry, transport and agriculture but also contributes significantly to a sustainable circular approach.

In addition to its positive contribution to greenhouse gas emission reduction, anaerobic degradation of biowaste generates organic soil improvers. Thus, biogas and biomethane become integral to a sustainable circular approach. Biomethane production supports the development of concepts for integrated circular cities in the EU, optimizing resource utilization.

This type of fuel is a key factor in the circular economy, creating opportunities for innovation and development in local economies. Over 600 scientific publications from various countries in the refereed international databases Scopus and Web of Science address the utilization of waste biomass, examining various aspects of the methanogenesis process, the influence of factors such as the composition and quality of the input raw material on the obtained biogas quantity. This underscores the scientific interest in issues related to energy generation from waste biomass.

A significant portion of the research involves the construction of laboratory models of biogas reactors and the study of their operation. For example, researchers from Pakistan [4] conduct a detailed study of biogas productivity in a laboratory installation mixing poultry and cattle manure. Different ratios of mixing the two manures yield varying results, with maximum productivity achieved at a poultry to cattle manure ratio of 1:3, resulting in a yield of 561 Nml/gmVS, more than twice that of the next highest yield. Additionally, the methane composition in the biogas is the highest at 64% CH<sub>4</sub>. The mixing of manures accelerates the biodegradation process, enhancing productivity, explained by the optimal C:N ratio of 20 ÷ 30. However, there is no explanation for the relatively long production process of 50 ÷ 63 days and the additional investigation of the thermophilic process –  $t = 45\text{ }^{\circ}\text{C}$ . Furthermore, the presence of lignocellulosic components – plant additives in the substrate is not commented on.

In the work [5], the optimization of biogas yield from a mixture of fresh poultry manure and maize silage is examined. The studies are conducted at different ratios of the input materials – 1:1; 1:2, and 2:1. They demonstrate the significant dependence of methane yield on the ratios of the input materials: in the case of a 2:1 ratio (poultry manure – maize silage), up to 53 % CH<sub>4</sub> is achieved, determining the optimal carbon-nitrogen ratio C:N to be 16 ÷ 18. The researchers also conclude that increasing the quantity of maize silage (lignocellulose) leads to an increase in the time of the anaerobic methanogenesis process and residence in the bioreactor (up to 60 days).

Serious research is also conducted by scientists from Slovenia [9] and [6]. The laboratory model of the biogas reactor consists of 12 bioreactors (fermenters) with an original device for separating and measuring biogas yield – a eudiometer. This design allows them to simultaneously investigate biogas production from substrates with different compositions and ratios. For example, in the cited study [9], the highest biogas and methane yield was achieved with a substrate of (75% sugar beet + 25% maize), resulting in a biogas yield of 493 NI/kg VS or 289 NI CH<sub>4</sub>/kg VS. Their studies confirm results over time: the majority of biogas is produced in the first week of the experiment, after twenty days anaerobic digestion is nearly complete, and after 35 days, the biogas production is very low.

In another study, [6], the production of biogas from six different energy crops (maize, sorghum, amaranth, sunflower, Jerusalem artichoke, and sugar beet) and swine manure (inoculum) is analyzed. According to the researchers, optimization of nutrients in the mixture is sometimes necessary by adjusting the C:N:P ratio of the input raw material mass to around 100:6:1. The highest yield is obtained with sunflower - 451 Nl/kg VS - which, with a methane concentration of approximately 62.85 %, means that the methane quantity is 283 Nl/kg VS, making it a valuable fuel for utilization. The substrate consists of 15 g of ensiled sunflower biomass and 385 g of inoculum (swine manure).

Despite numerous studies in the field of optimizing biogas production processes in biogas reactors, this scientific product, especially with precise descriptions and accurate research, remains relevant because:

- each geographical region, each country has the specifics of its agriculture - crop production (production of various fodder crops) and animal husbandry (farms for various animals);
- the production of agricultural products involves specific conditions such as selection, processing, fertilizing, feeding, irrigation, and other production conditions for plant and animal waste. And it is precisely this that necessitates more individual and specific optimizing technologies for biogas production in industrial biogas installations.

The aim of the present work is to create a laboratory research apparatus for a bioreactor for biogas production with capabilities for regulation and investigation of the impact of various parameters on the performance of the biogas installation. A pilot experiment will be conducted to validate its functionality.

## Research methodology

In [1] and [3], the authors describe their experiments in creating laboratory setups for generating closed-type, single-load biogas, which serve as the foundation for the present study.

Figure 1 presents the structural diagram of the newly created apparatus for a bioreactor for biogas, and Figure 2 shows an image of the apparatus.

The laboratory research apparatus for the bioreactor for biogas has the following research capabilities:

- Heating the organic substrate, regulating, and maintaining a constant environmental temperature in the range of  $t = 32 \div 42$  °C. This is achieved through an electric heater (2) with a power of  $P_{\max} = 150$  W and a temperature regulator (1). The control of the working temperature is conducted using a thermometer (5).
- Stirring the organic substrate using a mechanical (paddle) stirrer (14) driven by an electric motor (6), with the ability to adjust the rotation frequency of the stirrer in the range of  $n = 100 \div 200$  min<sup>-1</sup>. This ensures the necessary level of material stirring.
- Measurement of biogas production by volumetric method – displacement of water volume in a measuring vessel (reservoir) (11) through individual manual readings.

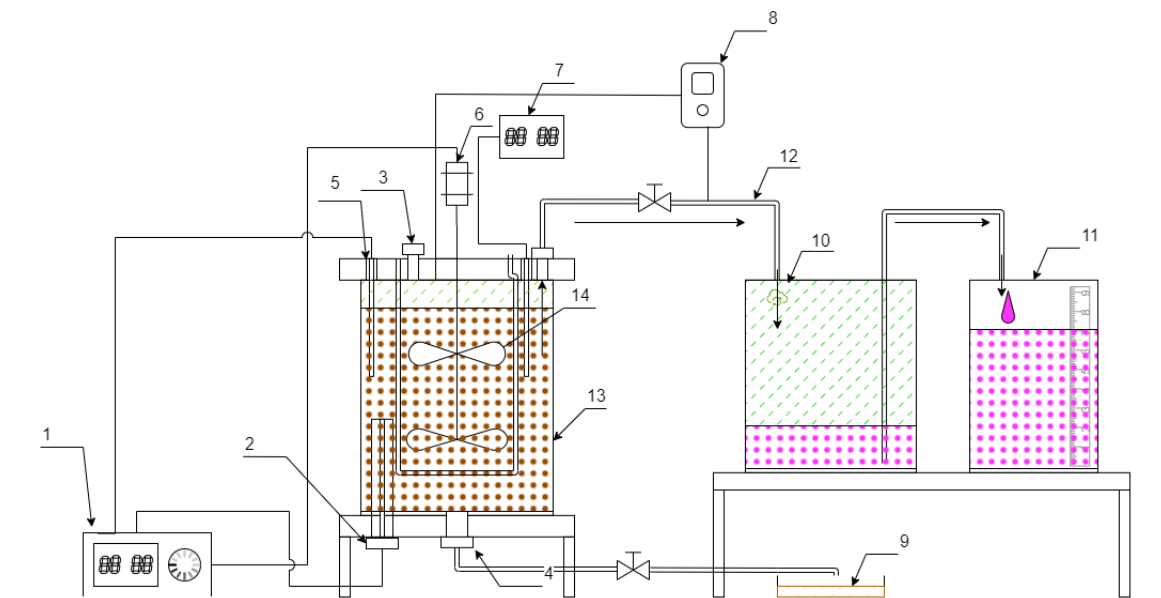


Fig. 1 Structural diagram of a laboratory apparatus for a biogas bioreactor 1 - control unit with thermostat and tachometer; 2 - electric heater; 3 - biomass loading port; 4 - technological drainage opening; 5 - thermometer; 6 - electric motor; 7 – pH meter; 8 – biogas analyzer; 9 - reservoir for drained biomass; 10 - gas holder; 11 – measuring vessel; 12 - pipeline for conveying biogas from the bioreactor to the gas holder; 13 – bioreactor; 14 - mechanical stirrer



Fig. 2 Laboratory research apparatus for a biogas bioreactor

- Measurement (control) of the pH level of the medium (organic substrate) using a pH meter (7) type VAT1011 (V&A);
- Analysis of the composition of the biogas produced in the bioreactor, using a biogas analyzer (8), type MS 400-4 (Beijing Zetron), which provides information about the relative content of gases: methane (CH<sub>4</sub>), carbon dioxide (CO<sub>2</sub>), hydrogen sulfide (H<sub>2</sub>S), and oxygen (O<sub>2</sub>) (in %);
- Working volume of the bioreactor (13) – with a charging material volume  $W = 1.8 \text{ dm}^3$ . With the bioreactor for biogas thus created, the following studies can be conducted:
- Single loading of the bioreactor and study over time until its biogas productivity is completely depleted – stationary mode;
- Multiple loading – periodic partial "loading - emptying" of the bioreactor (through input 3 and output 4 ports) and studying its productivity over time, as an actual model of a biogas installation – dynamic mode.

The biological substrate used in the experiment was obtained from an operational industrial biogas installation. This installation is fed by regional sources of animal and plant biological waste. The biological mixture (biomass) subjected to anaerobic biodegradation in the laboratory installation in the current study consists of three main components:

- Poultry manure - one of the main components of the mixture consists mainly of carbohydrates, proteins, lipids, and fiber, depending on the type of poultry feed.
- Corn silage - contains a large amount of lignocellulosic material, unsuitable as a sole raw material in the considered biological process (high C:N ratio). However, corn silage is highly productive when digested together with raw materials with a high C:N ratio, such as animal manure (chicken, cow, and pig). Co-digestion also ensures a more stable C:N ratio, pH, and maximum utilization of various types of waste.
- Fresh cattle manure – creates the necessary microbiological environment (inoculum) for the anaerobic biodegradation of biomass. The biological mixture also contains small amounts of press cake (a by-product of vegetable oil production).

The key characteristics of these components are provided in Table 1.

**Таблица 1. Характеристики на суровините в биологичния материал**

| №  | Biological material in the mixture | TS*, %  | VS**, % from TS | Gas productivity, l / kg VS | pH    | Ratio C :N |
|----|------------------------------------|---------|-----------------|-----------------------------|-------|------------|
| 1. | Fresh poultry manure               | 15 ÷ 25 | 75 ÷ 80         | 654                         | 6 ÷ 7 | 7 ÷ 10     |
| 2. | Fresh liquid cattle manure         | 6 ÷ 10  | 70 ÷ 80         | 400                         | 6 ÷ 7 | 20 ÷ 25    |
| 3. | Corn silage                        | 30      | 72              | 900                         | NA    | 40 ÷ 45    |

\*TS – Total solids, %

\*\*VS – Volatile solids (organic dry matter), %

The summarized general characteristics of the biological substrate are as follows:

- 9 % TS (Total Solids);
- 7 % VS (Volatile Solids);
- pH value: 7.2;
- Carbon-to-nitrogen ratio in the substrate C:N = 20.

After placing the biological substrate with a volume of  $W = 1.8 \text{ dm}^3$  into the bioreactor, the entire system is closed and sealed. The electric heater (2) and the mechanical agitator (14) are

activated and set to the necessary parameters for conducting the anaerobic digestion process -  $t = 37\text{ }^{\circ}\text{C}$  and  $n = 100\text{ min}^{-1}$ .

During the investigation, the following parameters are periodically recorded (daily or every 12 hours):

- Temperature in the bioreactor -  $t\text{ }(^{\circ}\text{C})$  using a thermometer (5);
- Hydrogen indicator - pH of the medium with a pH meter (7);
- Biogas yield  $W_i\text{ (m}^3, \text{ dm}^3\text{)}$  for the respective period - using a measuring vessel (11);
- Composition of the obtained biogas (%), using a biogas analyzer (8).

Throughout the study, attention is paid to maintaining a constant temperature in the biological environment in the bioreactor and monitoring the rotation speed of the mechanical agitator.

## Results of the biogas production investigation in the laboratory bioreactor

The main objective set by this study has been achieved – a functional laboratory model of a biogas reactor has been created, and the obtained results are consistent and in line with other research and biogas productions reviewed in the literature.

The primary outcomes from the initial investigation are presented in Table 2 and illustrated in Figures 3, 4, and 5. The composition of the produced biogas throughout the entire generated volume is detailed in Table 2. The results indicate a slight increase in the methane content in the gas mixture (an expected range of 58 – 63 %) and a decrease in carbon dioxide (an expected range of approximately 15 – 20 %). The explanation for this may require further investigation, possibly stemming from uneven composition in the "sample material" from the industrial biogas plant. Nevertheless, these results are accurate and remain uncompromised.

The created laboratory model proves to be a valuable tool for studying and understanding the dynamics of biogas production under controlled conditions. Further research is encouraged to delve into the factors influencing gas composition, ensuring the reliability of the results and providing insights for potential optimizations in industrial biogas production.

Table 2. Composition of the produced biogas

| Gas composition | CH <sub>4</sub> | CO <sub>2</sub> | O <sub>2</sub> | H <sub>2</sub> S |
|-----------------|-----------------|-----------------|----------------|------------------|
| %               | 68,55           | 10,23           | 1,56           | 0                |

The conducted study is presented in the following graphs, illustrating the dynamics of several characteristics of the produced biogas:

- Fig.3 - Increase in the overall production of biogas obtained in the laboratory bioreactor over time -  $W = f(\tau - \text{day})$ ;
- Fig.4 Variation in the productivity of biogas in the laboratory bioreactor over time -  $\dot{W} = f(\tau - \text{day})$ ;
- Fig.5 - Changes in the hydrogen indicator pH of the medium (substrate) in the laboratory bioreactor over time-  $pH = f(\tau - \text{day})$ .

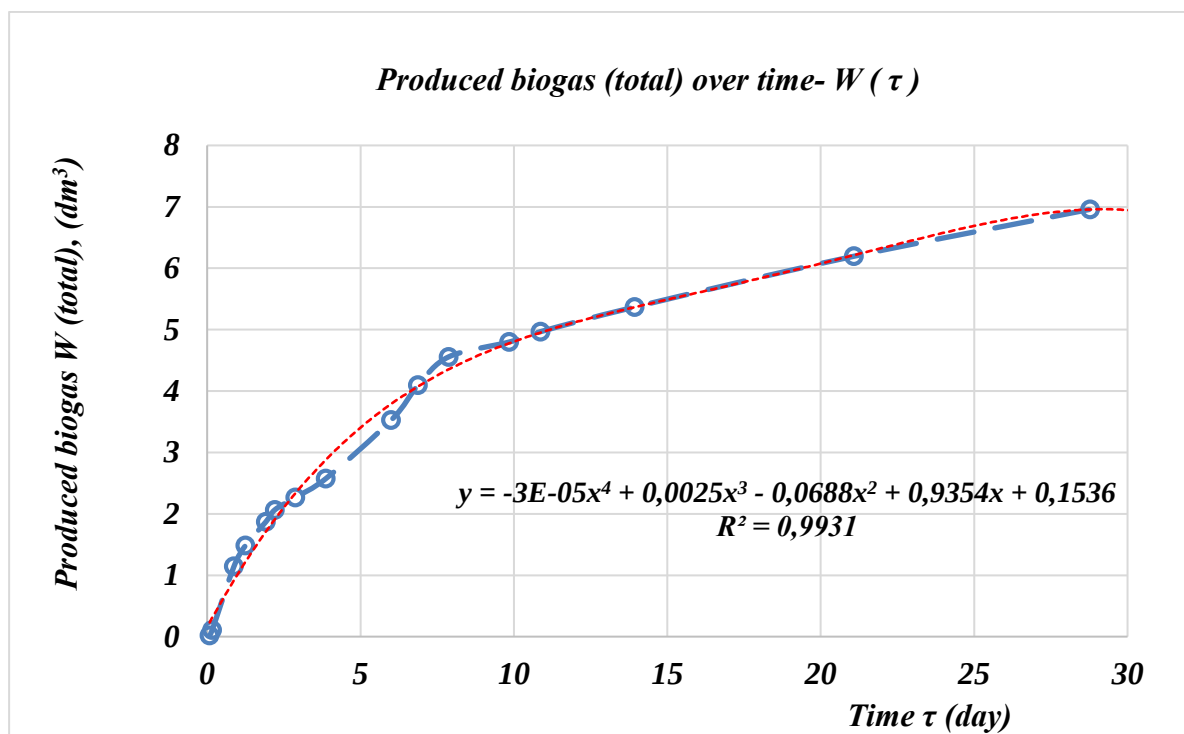


Fig. 3 Increase in the total production of biogas obtained in the laboratory bioreactor over time -  $W = f(\tau - \text{day})$

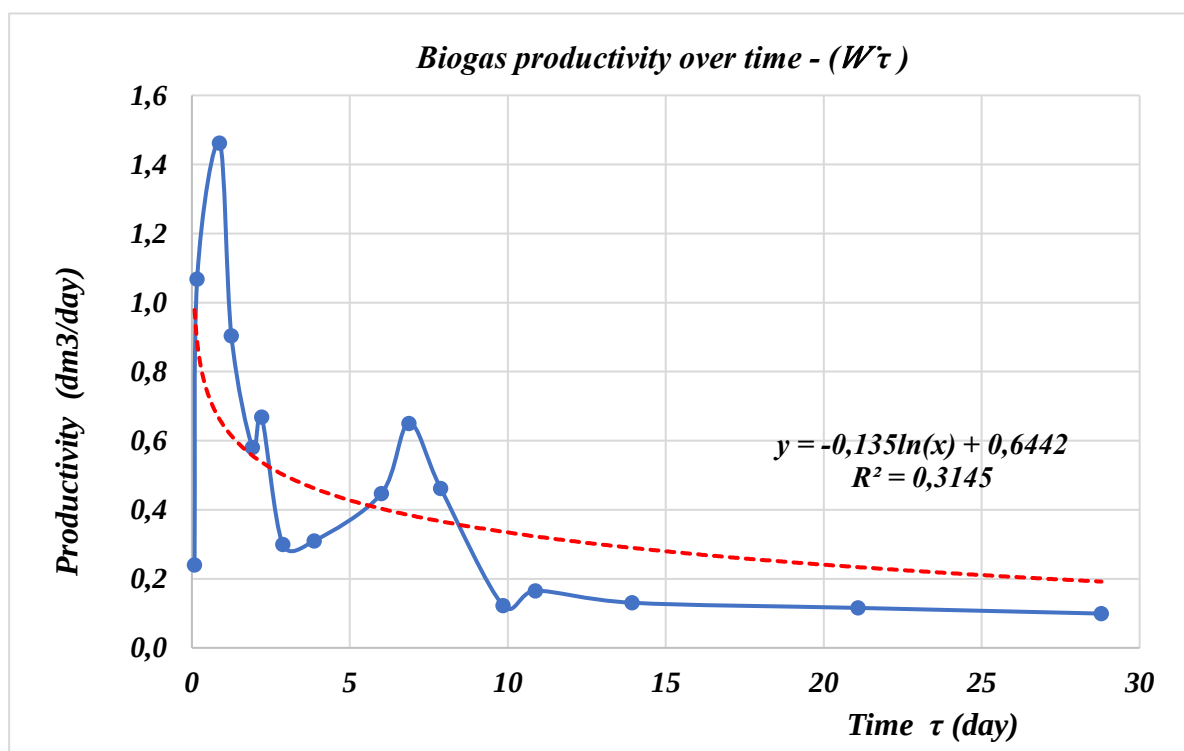


Fig. 4 Changes in biogas productivity in the laboratory bioreactor over time.  
 $\dot{W} = f(\tau - \text{day})$

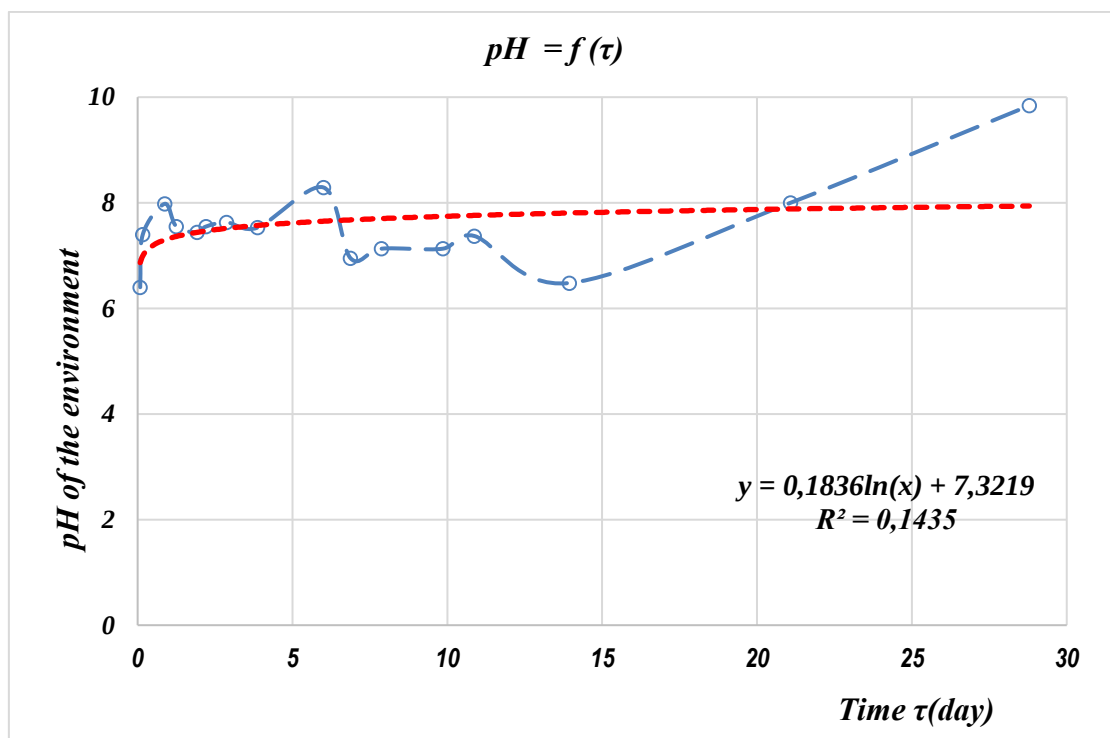


Fig 5 Variation in hydrogen indicator concentration (pH) of the medium (substrate) in the laboratory bioreactor over time  $pH = f(\tau - \text{day})$

### Analysis of the obtained results

The obtained results for the total produced biogas (Fig. 3) largely correspond to other studies - gradual increase in biogas production over time, with a decrease in the rate of increase after 10 days. In some other biogas productions, this dependency is very close to linear, indicating uniform production. The nature of this dependency is determined by the composition of the biomass (substrate) and the time required for the degradation of its elements. In this sense, the faster degradation of the studied mixture is explained by the presence of productive and faster-degrading poultry manure.

The total biogas production in the designed new laboratory research setup for a bioreactor for biogas production is  $W = 7 \text{ dm}^3$  for the entire described study. The study lasted for 30 days, and the specific biogas yield based on the characteristic of the biomaterial—organic dry matter - is  $55.5 \text{ Ndm}^3/\text{kg VS}$ .

The results presented in Fig. 4 represent the biogas productivity or the derivative of the biogas produced over time (from Fig. 3), i.e., the rate of biogas production. In reality, this rate is relatively high up to 6-7 days -  $\dot{W} = 0,4 \div 1,4 \text{ dm}^3/\text{day}$ , after which it significantly decreases to -  $\dot{W} = 0,1 \text{ dm}^3/\text{day}$ .

The uneven nature of the change in biogas productivity, these fluctuations around 3-6 days, can be attributed to possible issues with the continuous mixing of the biological substrate. Nevertheless, a clear trend of decreasing bioreactor productivity is evident.

A similar analysis can be conducted on the results for the change in pH of the medium—Fig. 5. These results fit coherently and explain some of the above conclusions. The anaerobic degradation process in the laboratory bioreactor is optimal at a medium pH around 7-8. However, when the pH of the medium increases beyond 8 after 20 days, the biodegradation process practically decreases significantly.

## Conclusion

The conclusions drawn from the conducted study and possible recommendations for further prospective research are as follows:

- I. Approach the investigations of anaerobic degradation and biogas production in the laboratory setup with a thorough preliminary study of the characteristics of each substrate component: determining the total solids (TS %), volatile solids (VS %), carbon-to-nitrogen ratio (C:N), and theoretical (or from other studies) specific potential yield from each substrate component ( $\text{Nm}^3/\text{t VS}$  or  $\text{Nl/kg VS}$ ).
- II. Enhance the laboratory setup to allow for the measurement of the composition of the currently produced biogas and automate the biogas yield reporting process. Consider improving insulation and darkening of the bioreactor in the installation.
- III. In planned studies, explore the characteristics of several different lignocellulosic materials—corn silage, sunflower silage, rapeseed material, and material from grapevine sticks—and technologies for various degrees of shredding these materials as substrate components.
- IV. The study revealed a multifactorial dependency, contributing to the complexity of optimizing the biogas production process, including:
  - The significant impact of pH on the degradation process, with an optimum around  $\text{pH} = 7-8$ .
  - The delaying effect of lignocellulosic materials on productivity, coupled with an increased yield in the bioreactor.
  - The necessity of strictly adhering to the optimal carbon-to-nitrogen ratio in the substrate  $(\text{C} : \text{N})_{\text{opt}} = 16-18$ .
  - The influence of continuous substrate mixing on installation productivity, considering issues like the formation of inhibitory crust or difficulties in separating produced biogas volumes.
  - The absolute and unconditional requirement to maintain a constant temperature in the bioreactor for methanogenesis realization, especially under mesophilic conditions ( $t \sim 35-37^\circ\text{C}$ ).
  - The observed varied biogas productivity over time, including process development, accelerated productivity, and gradual or abrupt declines in yield.

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