

Analysis of biogas production and prospects for the development of biogas technologies in Ukraine

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Abstract. The relevance of this study is determined by the fact that over the years the trend of finding new types of raw materials and technologies for their processing into biogas is growing rapidly. Not only people in European countries but all over the world tend towards the advantages of its production. For Ukraine, the development of infrastructure and a detailed study of this industry will later become a necessary stimulus for the reconstruction of the economy in the post-war period. The aim of the work is to analyze the biomass potential of fallen leaves for biogas production, taking into account the possibilities of technological development of this field in Ukraine. Several methods and approaches were used to achieve the goal. In particular, the physicochemical basis of the process of anaerobic fermentation of organic matter to obtain biogas was studied. A mathematical model of the process of obtaining biogas in a reactor from fallen leaves was also developed. And at the very end, the calculation of the economic efficiency of using a biogas plant for utilization of fallen leaves in a bioreactor was carried out. Summarizing the main results, it is possible to highlight the development of the patent-protected design of the bioreactor, the engineering methodology and the mathematical model for calculating the methane tank for the production of biogas from fallen leaves. First of all, the potential of biomass of plant origin for biogas production was analyzed and this led to the conclusion that the use of fallen leaves is a promising direction, but the significant advantages of using the raw material base are ignored. One of the main environmental problems of Ukraine remains the utilization of fallen leaves and other organic matter of plant origin. At the same time, the conducted research produces not only a number of solutions to this issue, but also turns the problem into an economically profitable solution and eliminates all ecologically unjustified processing methods

Keywords: gas holder; anaerobic fermentation; organic waste; raw materials; bioreactor

INTRODUCTION

The study of biogas technologies will create a powerful stimulus for the entire civilized world in the transition to renewable energy sources, since the production of

biogas consists in processing waste of organic origin. At the same time, the entire raw material base is quite diverse and under normal conditions is absolutely not

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involved, and when decomposed in the usual environment, it has a negative environmental impact. Unlike exhaustible sources such as oil or coal, the use of agricultural waste, food waste and wastewater will contribute to the transition to a more sustainable energy sector.

The utilization of organic waste and its successful processing will allow solving a number of environmental issues closely related to global warming, the manifestations of which are increasingly being observed on the planet. First of all, the active use and installation of biogas plants will contribute to the reduction of greenhouse gas emissions, namely methane. This malignant formation is observed during the natural decomposition of organic materials. The use of biogas technologies that capture and use methane can significantly reduce its emissions into the atmosphere, helping to reduce the greenhouse effect. On the other hand, the development of such technologies makes it possible to use organic waste effectively, which earlier would simply have been thrown away or subjected to a long process of natural decomposition. Instead, organic matter can be turned into a valuable resource – biogas and organic fertilizers. This helps to reduce waste, improve the management of agricultural waste and ensure sustainable development.

The analysis of the latest publications, which have already dealt with the research of similar aspects in this field, helped to understand the topic better, as well as to find problems that require additional and more thorough study. A publication by N. Pryshliak (2019) notes that India has an important place in the research, development and propagation of renewable energy technologies. Biogas production turned out to be a promising technology for processing agricultural waste into energy, including livestock, industrial and municipal waste. In 2017, gas consumption by the population of Ukraine amounted to 11.2 billion m³, while the potential value of biogas production from livestock waste is 1.5 billion m³ (13% of all consumed by the population).

According to Y. Gontaruk (2022), given Ukraine's negative trade balance and the country's great potential in the agricultural sector, the situation can be improved by focusing on the production of biogas from agricultural waste. One of the main producers of biogas can be sugar factories, the production of which can be restructured by building biogas plants. If the by-products of sugar mills are fully processed, they could produce about 790 million m³ based on their capacity in 2020, resulting in 473.7 million m³ of biomethane. This would make it possible to reduce the import of natural gas and provide sugar factories with their own source of energy.

According to L. Sakun *et al.* (2020), the most productive types of raw materials for biogas power plants are waste from farms and agricultural enterprises (silage, pulp, manure, litterfall, etc.), wastewater and household

waste from landfills. Ukraine has great potential due to high rates of development and low saturation of the agricultural market, which is the main source of bioenergy raw materials.

As noted by D. Tokarchuk *et al.* (2020), the use of biogas plants in Ukraine is effective for solving the problems of waste utilization, including crop production, improving the ecological situation, increasing soil fertility, reducing energy dependence and developing the economy locally. In addition, there is a significant group of raw materials in the perspective of application for biogas production, consisting of fresh grass, beet leaves, grass silage, corn and cereals, the output part of methane from which is from 270 to 330 l/kg.

Publication of M.K. Devi *et al.* (2022) is devoted to a review of recent advances in biogas production using agro-industrial waste. The work considers technical and economic aspects of this process. Biogas produced from agro-industrial waste can reduce greenhouse gas emissions, cumulative energy demand and environmental problems. During biogas production, some additives are added to the reactor to improve the biogas production process.

European scientists A. Sobczak *et al.* (2022) considered the economic conditions for biogas production on the example of Poland and Germany. Agricultural biogas plants that have been built in Western Europe, particularly in Germany, for over 20 years have been designed to use substrates derived from crops, mainly corn. Today, the trends have changed – the price of technologies that allow gas production mainly from agro-food industry waste is high. In general, the new plants will be more modern and better meet the objectives of the environmental policy of the European Union.

The purpose of this work was to study the peculiarities of the utilization of fallen tree leaves and the production of biogas from them as an alternative source of energy, as well as the development of the necessary technologies for the successful distribution of individual biogas equipment within Ukraine.

MATERIALS AND METHODS

The methodological basis of the researched topic was the application of theoretical and experimental regularities in the biochemical processes of anaerobic fermentation. During the multi-stage process of fermentation of organic compounds, the gradual destruction of carbon bonds occurs due to interaction with various groups of microorganisms.

In the process of biogas production research, an important aspect is the study of the materials involved in the researched object. That is why, for a deeper analysis, a comparison of the components of different types of organic waste was carried out, which will eventually become the necessary raw material base for the

production of an alternative source of energy, namely, biogas. In particular, raw materials collected on the basis of farm waste, vegetation residues, animal manure, as well as other organic products in the form of fallen leaves, grass, and sawdust were considered. A biogas plant was described as a research object for a complete technological review. The type of plant is based on the anaerobic fermentation process, which takes place in a special reactor. An anaerobic reactor looks like a closed container in which optimal conditions are created for the decomposition of organic substances by microorganisms without air access. After the fermentation process, biogas, consisting mainly of methane and carbon dioxide, is collected in the reactor and fed to the collection system, where it is stored in special containers, gas holders, where it can be used later for energy production or other purposes.

The following theoretical methods of scientific knowledge were used in this study of biogas: analysis of theoretical models, system analysis, optimization methods, kinetic modeling, genomic sequencing, gas chromatography and thermodynamic modeling. While analyzing various theoretical models, it was possible to get an idea of the processes taking place in biogas plants. At the same time, for more accurate results, mathematical models, physico-chemical calculations and analytical methods were applied. System analysis made it possible to investigate production processes from the point of view of energy and mass balance, as well as to evaluate the efficiency of the system and the relationships between components. Its application

included energy and mass balance analysis, as well as evaluation of the system's efficiency and the interconnections between its various components. The optimization method for process parameters is used to derive the optimal operating mode and maximize biogas production. Kinetic modeling helps to predict the speed and efficiency of biological processes depending on the studied parameters. In this study, it was involved in the development of mathematical models that essentially described the kinetics of biological processes, namely fermentation and methanogenesis in biogas plants. Genome sequencing allows studying microorganisms involved in the biogas process. Thanks to this method, it was possible to identify and categorize microbial communities and investigate their functional role in the biogas process. Gas chromatography (GCh) was used to analyze the composition of biogas and control the quality of production. In this work, the content of the following gases was investigated: methane, carbon dioxide, hydrogen. Thermodynamic modeling using thermodynamic models helped to study the thermal parameters and energy efficiency of biogas plants, as well as the conditions of optimal heat balance in biogas plants.

RESULTS

The key point affecting the rate of anaerobic fermentation is the conversion of acetic acid into methane during the decomposition of polymer-containing waste, which is limited to the hydrolysis stage. Figure 1 shows a scheme of methanogenesis, which shows the decomposition of organic substances.

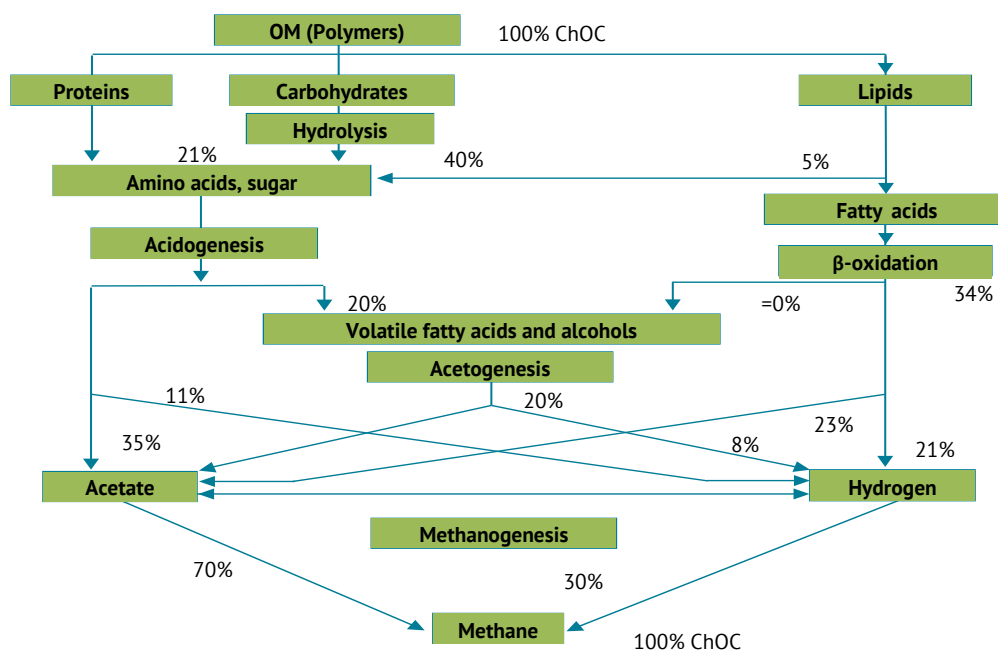


Figure 1. Complete scheme of methanogenesis

Note: ChOC – chemical oxygen consumption

Source: developed by the authors

To carry out the entire complex process of transformations, hundreds of types of microorganisms are involved, while the main role remains for bacteria. The quantitative and qualitative composition of microflora largely depends on the composition of fermented organic matter and environmental conditions. However, hydrolytic, fermentative, synthetic and methanogenic microflora predominate, which successively carry out the above-mentioned stages of anaerobic fermentation. In the course of studies of this process and design of plant models, empirical models of the process based on microbial kinetics and equations of the homeostat theory are used.

The Mono model is considered one of the most famous. It reflects the specific growth rate of microorganisms and the half-life of organic matter, which depend on many conditions of the fermentation process (1):

$$\frac{dx}{dl} = \frac{P_{max} \cdot X \cdot L}{K_1 + L}; \quad \frac{dl}{dt} = \frac{-P_{max} \cdot X \cdot L}{y(K_d + L)}, \quad (1)$$

where $y = dx/dt$ – mass conversion coefficient into biomaterial; dx/dl – growth of microorganisms, day^{-1} ; X – microbial population density, kg/m^3 ; L – saturation of the substrate, kg/m ; dl/dt – change in biomass density, day^{-1} ; P_{max} – the highest rate of reproduction of microorganisms, day^{-1} ; K_1 – the half-saturation threshold of the substrate concentration, at which the rate of the process reaches half the maximum level; K_d – indicator of biomaterial decomposition.

This model has limitations in working with different types of substrates. Another attempt to mathematically describe the process of methane fermentation is the model presented by Muyang (2):

$$P = \frac{L}{1 + 10^{(pK - pH)}} \cdot \left(\alpha - \beta \frac{K_\tau}{1 + K_\tau} \right) \cdot \frac{\text{HM}^3}{\text{M}^3}, \quad (2)$$

where P – specific rate of biogas removal; L – list of initial organic compounds, kg ; K_τ – period of complete interchange of initial material, day ; α, β – coefficients that depend on the nature of the carbohydrate component, the type of substrates and the content of organic nitrogen in the waste; pK and pH – constants, depending on the temperature regime, day^{-1} .

The above Muyang model demonstrates the influence of the organic composition of the original substrate on the intensity of the fermentation process by distinguishing between the hydrocarbon fraction and the content of organic nitrogen compounds. For a wider class of input substrates, taking into account the volume rate of biogas and essential parameters of the methane fermentation process, the Kanto model (3) is used:

$$V = \frac{B_0 \cdot S}{T} \left(1 - \frac{K}{\mu \cdot T - 1 + K} \right) \cdot \frac{\text{HM}^3}{\text{M}^3}, \quad (3)$$

where V – speed of the output volume of biogas, $\text{m}^3/(\text{m}^3 \cdot \text{day})$; B_0 – the maximum amount of biogas release from a unit of organic matter of the established composition after an infinite duration of exposure, m^3/kg ; S – concentration of organic matter in the source material, kg/m ; T – exposure time, day ; μ – the greatest growth of microorganisms during the fermentation process, day^{-1} ; K – kinetics.

The highest growth of microorganisms (μ) is described by a linear dependence of temperature values from 30 to 60°C. In his research, Hashimoto derived an empirical formula that describes the dependence of the process temperature on the kinetic parameter K and the exposure time in regimes involving tolerant ($T = 45^\circ\text{C}$) and thermophilic ($T = 60^\circ\text{C}$) regimes (4):

$$K = [-0.95 - 0.51 + 0.01(T) + 0.0004(T^2)]. \quad (4)$$

The calculation of biogas yield according to the Hashimoto model can be determined by formula (5):

$$\gamma \cdot V_{max} = \frac{B_0 \cdot S_0 \cdot M_n}{(1 + \sqrt{K})^2}, \quad (5)$$

where K – kinetic parameter; B_0 – the maximum output of biogas from a single given organic substance under the condition of an infinite exposure index, m^3/kg ; S_0 – initial content of organic matter in biomass, kg/m ; M_n – growth rate of microorganisms in a given fermentation process, day^{-1} .

Then, in the initial substrate, the dependence of the values of the kinetic parameter on the concentrations of organic matter is described as follows (6):

$$K = 0.5 + 0.03 \exp(0.058). \quad (6)$$

The balance of bacteria in the fermented substrate (7):

$$\frac{dx}{dt} = \mu \cdot x - D \cdot x, \quad (7)$$

where x – bacterial density, kg/m^3 ; D – rate of dying, day^{-1} ; μ – rapid growth, day^{-1} .

In his work, Hill expanded the Kanto model by adding the coefficient K , which takes into account the loss of microorganisms in the fermentation process (8):

$$\gamma \cdot V = \frac{B_0 \cdot S_0}{\theta} \left[1 - \frac{K(1 + K_d \cdot \theta)}{\theta \cdot \mu - (1 - K_d \theta) - (1 - K)} \right], \quad (8)$$

where θ – time of exposure of the substrate in the methane tank; $\theta = \frac{V}{VS}$. The loading speed of the methane tank with organic matter is indicated $\frac{V}{VS}$, where VS – the period of obtaining volatile solids from the farm, which depends on the number of animals and their diet; V – methane tank capacity.

In the above mathematical models of anaerobic fermentation, there is a mathematical parameter S , which

indicates the concentration of organic matter in the source material and gives the values of empirical coefficients that take into account individual cases of biogas extraction from the components of the source substance.

Empirical engineering and mathematical models are most often used in the production of biogas, provided that regression dependencies are derived taking into account the characteristics of a certain type of biomass. Therefore, when using these models, it is advisable to conduct experiments to determine empirical coefficients.

In order to implement the process of processing waste into gas inside the biogas plant, several important measures must be taken. First, it is necessary to ensure the access of nutrients to the bacteria, constant oxygen-free and temperature conditions, the correct ratio of solid particles in the substance and high-quality mixing. Secondly, monitor the ratio of carbon and nitrogen in the mass, the fermentation time and timely loading and unloading of raw materials, as well as the absence of inhibitor substances in the content.

During the multi-stage fermentation process of methanogenesis, the destruction of carbon bonds occurs. Various groups of microorganisms contribute to this, so the biogas production process is carried out in four stages:

- the stage at which complex molecules of biopolymers (proteins, lipids, polysaccharides) are hydrolyzed to simpler monomers (amino acids, carbohydrates, fatty acids);

- the stage at which the resulting monomers undergo fermentation to simpler substances, such as lower acids and alcohols, with the formation of carbon dioxide and hydrogen;

- acetic acid production stage: acid, hydrogen and carbon dioxide are produced, which in turn are direct precursors of methane;

- stage of methanogenesis: the decomposition of complex organic substances with the formation of methane as the final product (Abbasi *et al.*, 2012).

Anaerobic fermentation for the production of biogas is a complex biotechnological process, which requires interaction and fulfillment of the following

conditions for the effective course of methane fermentation of organic substances: the appropriate temperature regime of the process; weak alkaline reaction of the environment; the presence of methane-forming bacteria; oxygen-free environment.

One of the important factors of an effective fermentation process is the temperature regime of the fermenting biomass. The natural release of biogas takes place at a temperature from 0°C to 98°C, taking into account the process of optimized processing of organic substances for the purpose of removing biogas and biofertilizer while maintaining three temperature regimes: psychrophilic (20-25°C); mesophilic temperature regime (25-40°C); thermophilic temperature regime (more than 40°C) (Mao *et al.*, 2015).

Depending on the selected mode, for a high-quality fermentation process in the bioreactor, the same temperature level should be maintained and biomass should be regularly mixed. Also, when choosing a thermophilic mode, it is worth considering its significant advantages compared to others – with accelerated decomposition of raw materials, the complete destruction of disease-causing bacteria, as well as obtaining a larger amount of biogas at the output. Disadvantages include high energy consumption, initial low-quality biofertilizer, and significant sensitivity to minimal temperature changes. Due to these negative factors, a mesophilic temperature range is used for European fermentation chambers.

Another important factor in methane fermentation is the dependence of the content of raw materials between nitrogen and carbon. A lack of nitrogen and an excessive indicator of the C/N ratio will lead to limitations in the process of methane formation (Table 1). At the same time, a small indicator of the mentioned ratio, in turn, will lead to the formation of a large amount of ammonia, which is toxic to bacteria. Experiments have shown that the level of the ratio of carbon and nitrogen from 10 to 20 (depending on the origin of the raw materials) stimulates to achieve the highest degree of gas formation (Kougias *et al.*, 2014).

Table 1. C/N ratio of organic waste that can be a raw material for obtaining biogas

Raw material for biogas	Nitrogen, %	The ratio of carbon to nitrogen, C/N
Animal manure		
Cattle	1.7; 1.8	16-25
Chicken	4-6	7-10
Horse	2	25
Swine	4	6-12
Sheep	4	33
Household waste		
Feces	6-7	6-10

Table 1, Continued

Raw material for biogas	Nitrogen, %	The ratio of carbon to nitrogen, C/N
Household waste		
Kitchen waste	2	29
Potato peels	1.5	25
Cabbage	4	13
Tomatoes	3	13
Vegetation waste		
Corn cobs	1	57
Cereal straw	1.0	50
Wheat straw	0.5	100-150
Corn straw	0.7	51
Oat straw	1.0	50
Soy	1.3	33
Alfalfa	2.8	16-17
Beet pulp	0.3-0.4	140-150
Others		
Grass	4	13
Sawdust	0.1	200-500
Fallen leaves	1.0	50

Source: developed by the authors based on P.G. Kougiaris *et al.* (2014)

The process of processing organic substances into biogas is called methane fermentation. Based on anaerobic fermentation by splitting biomass with bacteria (methanogens). There are 4 types of bacteria involved in the formation of biogas (Fig. 2).

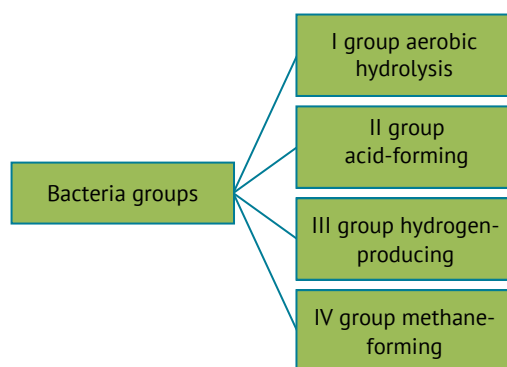


Figure 2. Bacteria involved in the process of biogas formation

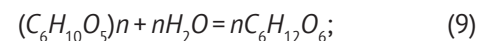
Source: developed by the authors

Metabolites from all groups of bacteria provide nutrients to each subsequent group. In particular, the first group of bacteria uses enzymes to convert organic compounds (proteins, carbohydrates, and fats) into low-molecular compounds (water, fatty acids, and amino acids). Acid-forming bacteria convert these low-molecular compounds into unstable fatty acids (acetic,

formic, propionic), ethanol, carbon and gases (carbon dioxide, hydrogen, hydrogen sulfide, ammonia). Hydrogen-producing bacteria are responsible for the conversion of higher fatty acids into acetic and formic acids, carbon dioxide, and hydrogen. The fourth group of bacteria (methane-forming) process acetic and formic acids into methane (Vindis *et al.*, 2009).

The process of anaerobic fermentation is accompanied by a number of biochemical reactions, and the process of biogas formation itself consists of three sequences:

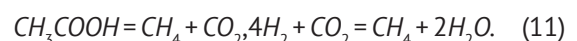
I stage – hydrolysis – is the decomposition of organic substances (9):



II stage – acetogenesis – is the reproduction of acid-forming bacteria (10):



III stage – methanogenesis – is the reproduction of methane-forming bacteria (11):



At the initial stage of anaerobic fermentation, hydrolytic bacteria enzymatically split polymers into low molecular weight formations. Polymers (multi-molecular compounds) are converted into monomers (monomolecular). A feature of the described hydrolysis

process is time-consuming and dependent on extra-cellular enzymes, namely protease, amylase and lipase. In the bioreactor, hydrolysis is also influenced by the potential of hydrogen ions.

At the stage of acetogenesis, acid-forming bacteria are engaged in splitting. This stage of methane fermentation is called oxidation, during which the potential of hydrogen ions decreases. Individual molecules penetrate into the bacterial cell and continue to split there. Aerobic bacteria partially participate in this process by consuming residual oxygen to create the anaerobic conditions necessary for methanogenic bacteria, some of which become anaerobic. At this stage, such gases as unstable fatty acids (acetic, formic, butyric, propionic), low-molecular alcohols (ethanol, methanol), carbon, carbon dioxide, hydrogen, hydrogen sulfide, and ammonia are formed. In addition, hydrogen-producing bacteria utilize organic fatty acids to produce acetic, formic acids, carbon dioxide, and hydrogen for methanogenesis. Such bacteria are very sensitive to temperature, as they reduce the amount of carbon (as part of organic acids) (Bacenetti *et al.*, 2013).

The last stage of methane production by methanogenic bacteria involves splitting into carbon dioxide and water from formic and acetic acids, hydrogen and carbon. At this stage, 90 percent of all methane is formed, while only 70% is produced from acetic acid. It should be noted that methane-forming bacteria are exclusively anaerobic. Thus, the process of anaerobic fermentation is influenced by four factors:

- biological (the composition of the fermented mass, the composition of the microflora, the living conditions of organisms);
- physical (fermentation temperature, biogas plant pressure, hydraulics);
- chemical (concentration, acidity of the environment, volume and composition of the formed biogas);
- organizational and technological (volume of loading biomass, residual substances).

Modern biogas plants consist of the following main elements:

- system of preparation and supply of raw materials to the bioreactor;
- bioreactor with raw material mixing and heating systems;
- system of unloading and transportation of fermented waste;
- biogas storage and use system (Meyer *et al.*, 2018).

The main unit of a bioenergy plant for biogas production is a methane tank (bioreactor). The main requirements of methane tanks include: technological, hydraulic, thermal and economic. The main criteria

when choosing a bioreactor design are the possibility of its practical application, economic feasibility and convenience of its maintenance and operation. As of 2023, the market offers a variety of bioreactors by design. The classification of methane tanks is shown in Figure 3.

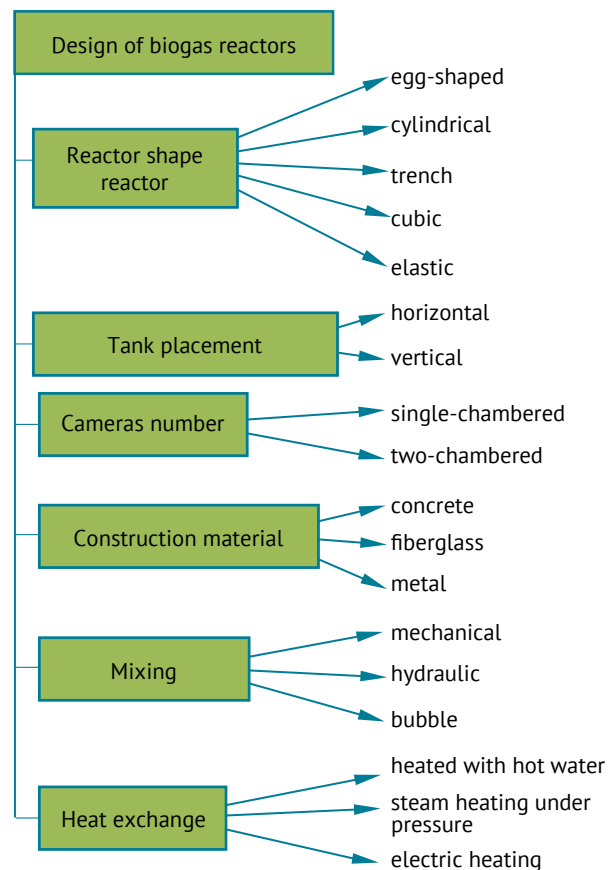


Figure 3. Classification of biogas reactors by structural features
Source: developed by the authors

A biogas plant is a complex of constructions and technical support combined into an autonomous process of anaerobic fermentation for the production of biogas. It can be installed both indoors and outdoors, fixing it with a foundation or the ground. Essential requirements for its structure are compliance with hermeticity and corrosion resistance, the installation of a hatch in the model is provided for.

Biogas complexes can be divided into one- and two-staged. The first ones are more common and basic, because they are suitable for many substrates. The second ones are more complicated due to an additional hydrolysis reactor. They are used for rapidly decomposing working material that is easily oxidized (Tabatabaei & Ghanavati, 2018). The basic equipment of the biogas plant is shown in Figure 4, and a detailed description of the depicted construction nodes is given below.

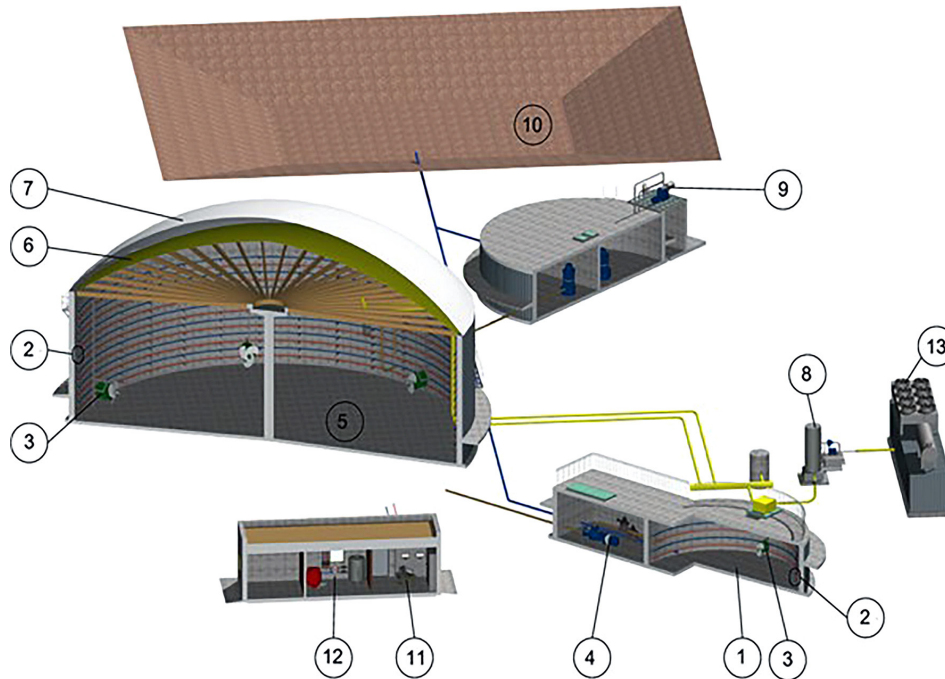


Figure 4. Structure of the biogas plant

Notes: 1 – receiving container; 2 – heating system; 3 – mechanical stirrers; 4 – biomass supply system; 5 – fermenter; 6 – gas holder; 7 – dome; 8 – gas removal and gas supply system with condensate removal and sulfur purification system; 9 – separator; 10 – liquid fertilizer storage tank; 11 – automation system, visualization of processes and management; 12 – heating point; 13 – generator

Source: developed by the authors

Maximum automation and minimum manual work is the basic principle of this installation. The material for reducing the volume to be processed enters the receiving container (1). This container is used for pre-settling, heating (2) and thorough mixing (3). The raw material is fed to the fermenter (5) several times a day. The fermenter (5) is a sealed, gas-tight tank. To maintain a stable temperature, the inside of the methane tank is equipped with a heating system (2). In the cold season, the bioreactor is insulated from the outside to prevent heat loss. Continuous mixing of the substrates using a low-speed mechanical stirrer (3) ensures complete and thorough mixing of the raw materials. Physicomechanical methods applied to substrates use different types of mixing systems, such as mechanical, hydraulic or pneumatic.

Fermented substrate is automatically discharged as often as it is fed. The operation process of the biogas plant is generally controlled by an automation system (11). The produced biogas is collected and stored in a gas holder (6). They are used as a gas-tight element for the fermenter, which serves as a gas storage tank. The outer dome roof (7) is UV resistant, fire resistant and easily scalable. The design of the biogas plant ensures high flexibility of this element and reliable fixation of the plant. Biogas is transported through the pipeline (8), which is equipped with an automatic condensate drain and a safety device that protects the gas holder

(6) from exceeding the allowable pressure. The gas holder (6) continuously supplies biogas to the cogeneration plant or the biogas preparation plant. Then the processed substrate is fed to the separator (9). The mechanical separator works 4-6 times a day to separate the fermentation residues into solid and liquid fertilizers. All equipment is controlled by the automation system (11). The design of the biogas plant minimizes the need for manpower during operation. The heating point (12) in the biogas plant helps ensure energy-efficient use of biogas, which is a renewable energy source. It allows you to make the most of the potential of biogas by converting it into thermal energy. The generator (13) is designed to convert the mechanical energy obtained from the movement of the engine into electrical energy. In a biogas plant, a generator uses biogas as a fuel to drive an engine that rotates the generator and produces electricity (Misak *et al.*, 2014).

Signals regulating the operation of the entire plant are sent to the central programmed logic controller. The controller regularly polls all elements of the combined technological chain and displays the information on the monitor screen. All constructions and components, as well as drives and parameter sensors are displayed on the monitor screen. All operating parameters of the biogas plant are displayed on the monitor in the central control room. The control room has a central

control panel, from which all parts of the biogas plant can be switched between automatic and manual modes of operation, as well as controlled locally or remotely (Geletukha *et al.*, 2013).

The analysis of the results obtained in the above-described experiment led to a number of conclusions regarding the technological aspects of biogas production. In particular, the first and most important is the correct preparation of the substrate. This stage involves the preparation of raw materials used for biogas production. This may involve dissolving, grinding or enzymatically treating the feedstock to facilitate the biogas fermentation process. Next, the substrate that has been prepared is subjected to the fermentation process. In this stage, microorganisms, such as bacteria or anaerobic fungi, decompose organic substances in the substrate and release biogas. Biogas, which is formed during fermentation, is collected and stored in special containers or tanks. It can be a gas holder or compressed gas cylinders. It should also be taken into account that biogas often requires processing and purification before use. This includes removing contaminants such as moisture, hydrogen sulfide, or other impurities that may adversely affect the quality of the gas or equipment. Well, at the very end comes the effective use of the final product. Purified biogas can be used to produce heat, electricity or in processes that require gas as a fuel. This may include the use of biogas in a boiler room for heating, a combustion plant for electricity production or use in manufacturing processes.

A general overview of the sphere of biogas production in Ukraine leads to the following conclusions. The development of biomass processing technologies for biogas production is constantly being improved. The use of highly efficient biogas plants, optimization of fermentation processes and purification of biogas allow to increase production efficiency and reduce environmental impact. The production of biogas from the biomass of fallen leaves can have significant economic benefits. This can create new workplaces, attract investment and promote the development of rural and forest areas. The use of biomass for biogas production in Ukraine can help achieve energy independence, reduce greenhouse gas emissions, and develop a sustainable energy sector.

DISCUSSION

Many scientists were engaged in the study of anaerobic fermentation and establishment of regularities for the calculation of biogas plants. However, given the chemical complexity of realizing the interaction between groups and species of bacteria and the diversity of substrate components, the laws of the methane

fermentation process are extremely complex and largely unexplored. In the practice of research, the development of anaerobic fermentation technologies is based on empirical models of the process, which in turn are based on the equations of microbiological kinetics and the theory of the homeostat.

An example for the discussion of this thesis is the study of authors S. Ma *et al.* (2021), in which, using detailed sequencing of digestate samples from 56 full-scale biogas plants (BGPs) processing different feedstocks, they presented a microbial anaerobic fermentation (AF) gene catalog containing more than 22.8 million genes with attached information on their role in cellular processes. The results confirm the presence of a core microbiome in AF and show that the type of raw material (cattle manure, poultry manure, pig manure) has a significant effect on the breakdown of carbohydrates by hydrolysis, oxidation of volatile fatty acids and methane production. In addition, 2,426 genomes assembled from metagenomic data from full-scale BGPs were also provided. Compared to previously published catalogs of microbial genes from various ecosystems, including soil, marine environments, gut, and animal rumen, BGP is an artificial highly anaerobic ecosystem where AF is carried out by a complex community of anaerobic microorganisms. Therefore, their gene list not only serves as a valuable reference base for rapid analysis of microbiome data in AF, but will also provide a rich source of microbial genes for the study and use of anaerobic microbiota.

A study published by K. Pilarski *et al.* (2020), describes the process of yielding methane obtained from corn silage, pig manure, potato waste, and sugar beet pulp. An original methodology for determining the Biochemical Methane Potential Correction Coefficient (BMPCC) based on biomass conversion calculations at industrial and laboratory scales is also presented. BMPCC is a tool that can be used to increase the efficiency of biogas plants and avoid unnecessary losses. The calculated BMPCC values showed that the amount of methane produced in the laboratory was overestimated compared to the amount of methane according to specifications. Differences were observed for each substrate.

In the study of M. Fugol *et al.* (2023), the authors studied the use of enzyme additives in anaerobic fermentation and concluded that in the case of corn silage, the use of additives increased the efficiency of the adsorption process compared to the control in the range of 17 to 62%, depending on the additive used. In the case of silage, *igniscum* produced more biogas and grass silage showed a decrease in biogas production efficiency compared to the control (no additives)

sample, but it increased methane production in corn and grass silage. It is noted that bio-additives lead to improved energy performance, but this depends on the agricultural substrates and additives used.

The work published by scientists S. O'Connor *et al.* (2021) confirms that small-scale anaerobic fermentation is a promising renewable energy technology for agriculture. Bioenergy is profitable due to the possibility of producing biofertilizers and reducing emissions into the atmosphere. Issues related to plant design, energy use, political implications and barriers were discussed. This study examines the current state of small-scale anaerobic fermentation technology in Europe, identifying process flow and performance characteristics, the impact of European Union policies, recent developments and the challenges they face.

At the same time, S. Cinar *et al.* (2022) in the course of their research concluded that process optimization is already a prerequisite for market viability in all sectors. This statement is also relevant to anaerobic fermentation in bio-plants. The benefits of using renewable energy plants can be extended by more technologically advanced and less expensive systems, with the overall goal of minimizing costs and maximizing process efficiency. With the help of data science and predictive analytics, traditional methods of process optimization and operational excellence, statistical process management can be taken to a new level. The more perfect the optimization of the process, the more transparent and more sensitive the system becomes. In the study, laboratory results were compared with several separate machine theory procedures (logistic and linear regression, K-NN, decision trees, random forests, direct vector machines (SVM and XGBoost)) to detect and predict a wide range of possible temperature fluctuations on process stability. According to measured by the accuracy of the models calculated according to the principle of the error matrix, SVM provided the best accuracy – 0.93.

Based on the conclusions made as a result of research, it can be said that the problem of producing biogas from secondary material for energy supply is urgent, that is why the works of international and Ukrainian scientists are dedicated to it. At the same time, the introduction of innovations to reduce the negative impact on the environment has not been implemented sufficiently. The methods of waste processing with electricity generation need to be optimized primarily at the regional levels. This implies a clearly expressed need for conducting additional research in this field and carrying out specific calculations of economic and environmental benefits from waste processing for the production of biogas in Ukraine and its regions.

CONCLUSIONS

The main sources of biogas production are products, plant and animal husbandry waste. As a result of the review, it was established that the problems of the rational use of animal waste were considered in many scientific works, but at the same time, due attention was not paid to the processing of plant waste, in particular, the disposal of fallen leaves and dry grass. This confirms the perspective in the use of biological leaf waste and the hypothesis that the raw material base itself is not used enough.

In autumn, an ecological problem in the cities of Ukraine is the utilization of fallen leaves. The most common methods of utilization of fallen leaves in Ukraine are: in the best case, it is unloading solid household waste at suburban landfills; at worst it is burning, which leads to atmospheric pollution (prohibited by law). Removal of leaves to landfills requires significant costs, and when burned, harmful substances are released (nitrogen oxide, carbon monoxide, benzopyrene, formaldehydes, and others). That is why it is appropriate to consider that the most acceptable solution to the problems with the utilization of fallen leaf residues is biodestruction under anaerobic conditions. Such a means of processing foliage is not only environmentally safe, but also economically justified, because the biogas formed in the process of methane fermentation can be considered an alternative source of energy, and fermentation waste can be considered a valuable biofertilizer.

The analysis of scientific and technical literature made it possible to determine the main factors affecting the process of anaerobic fermentation in the production of biogas from fallen leaves, which requires technological improvement of the equipment in order to ensure the maximum value of the final product and to substantiate the cost-effective utilization of organic waste with the production of biogas and organic fertilizers.

Having considered the modern designs of gas bioreactors, we can conclude that the main criteria for choosing a methane tank for the disposal of fallen leaves are the possibility of using it in practice, its economic feasibility and the convenience of its maintenance during operation. To obtain biogas from fallen leaves, the most optimal design is an egg-shaped bioreactor. Its shape reduces hydraulic resistance when mixing raw materials and allows you to avoid stagnant areas thanks to aerodynamic design. Optimizing the technical parameters of bioreactors will lead to the maximization of the amount of biogas from a unit volume of biomass (foliage) and will increase productivity indicators. Their formation is influenced by the system of mixing and heating the substrate. When choosing a mixing system,

it is necessary to take into account its effect on the rate of methane formation and the fermentation time of biomass in the methane tank. To reduce the influence of environmental temperature fluctuations and achieve thermal stability in methane tanks, you can resort to thermal insulation of the walls of the bioreactor at the same time as heating the biomass.

The development of biogas plants in Ukraine is an important step on the way to sustainable development and the use of renewable energy sources. Work is needed to improve fermentation and gasification processes to produce more biogas from different types of organic matter. Further experiments can be aimed at optimizing the fermentation conditions, increasing the efficiency of the reactors and reducing the processing time. Another important aspect of research is the use of new types of raw materials. In experiments, it is possible to develop methods of utilization of various types of raw materials, such as agricultural waste, municipal waste and other organic materials. For each raw material, it is necessary to determine the optimal conditions for its transformation into biogas and to investigate the effectiveness of this process. It is also possible to

focus on the development of effective systems for waste management and monitoring of gas emissions from biogas plants, including methods of removing hazardous substances. It is important to conduct an evaluation analysis of costs for biogas production and develop business models and financing strategies. In addition, such research can contribute to political support and regulation of the development of biogas plants. Focusing on the development of effective mechanisms will stimulate development in the biogas industry, in particular, it will have an impact on tax incentives, support for government programs and development strategies. It is expected that these areas of research will contribute to the further development of biogas plants in Ukraine, providing a sustainable source of energy, reducing greenhouse gas emissions, and promoting the country's economic development.

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CONFLICT OF INTEREST

None.

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Аналіз виробництва біогазу та перспективи розвитку біогазових технологій в Україні

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Анотація. Актуальність цього дослідження зумовлена тим, що з роками тенденція пошуку нових видів сировини і технологій для їх переробки в біогаз стрімко зростає. До переваг у його виробництві схиляються не лише в європейських країнах, а й у всесвітніх масштабах. Для України розвиток інфраструктури та детальне дослідження цієї галузі згодом стане необхідним стимулом для відбудови економіки в післявоєнний час. Метою роботи є проведення аналізу потенціалу біомаси опалого листа для виробництва біогазу, враховуючи можливості технологічного розвитку даної сфери в Україні. Для досягнення поставленої мети застосовано кілька методів та підходів. Зокрема, було вивчено фізико-хімічні основи процесу анаеробного бродіння органіки для отримання біогазу. Також здійснювалася розробка математичної моделі процесу отримання біогазу в реакторі з опалого листа. І на сам кінець, проведено розрахунок економічної ефективності застосування біогазової установки для утилізації опалого листа в біореакторі. Підсумовуючи основні результати, можна виділити розробку патентно захищеної конструкції біореактора, інженерної методики та математичної моделі розрахунку метантанку для виробництва біогазу з опалого листа. Передусім було проаналізовано потенціал біомаси рослинного походження для виробництва біогазу і це привело до висновку, що застосування опалого листа є перспективним напрямком, проте значні переваги використання сировинної бази ігноруються. Однією з основних екологічних проблем української держави залишається утилізація опалого листа та іншої органіки рослинного походження. В той же час, проведене дослідження продукує не лише ряд вирішень цього питання, а й перетворює проблему на економічно вигідне рішення і нівелює всі екологічно не виправдані методи переробки

Ключові слова: газгольдер; анаеробне бродіння; органічні відходи; сировина; біореактор