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# TECHNOLOGY FOR PRODUCING BIOGAS AND ORGANIC FERTILIZERS FROM BIOETHANOL INDUSTRY WASTE

***Introduction.*** *One of the viable approaches to supplementing and partially replacing natural gas is the utilization of biogas. Biogas is produced from organic feedstocks through biomethanogenesis and has a composition comparable to that of natural gas.*

***Problem Statement.*** *The production of 1 $m^3$ bioethanol generates approximately 10—15 $m^3$ vinasse, a high-strength liquid waste commonly disposed of in filtration fields. Vinasse can serve as a valuable feedstock for biogas production, enabling bioethanol plants to achieve partial energy independence. The capital costs associated with biogas plant installation can be recovered through energy generation and the avoidance of environmental pollution penalties.*

***Purpose of the Study.*** *The purpose of this study is to develop a biotechnology for the utilization of vinasse in combination with a lignocellulosic co-substrate for the production of biogas and organic fertilizers at bioethanol plants, addressing challenges related to alternative energy supply and waste management in Ukraine.*

***Materials and Methods.*** *The moisture content was determined by oven drying at 105 °C, the ash content by combustion at 550 °C, the total nitrogen by the Kjeldahl method, the sulfur content by complexometric titration, and the microelement composition by atomic absorption spectrometry. Vinasse,*

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*sweet sorghum bagasse, and digestate have been investigated as substrates for biogas production. Methane fermentation has been studied under mesophilic conditions with periodic loading. Biogas yield has been measured by volumetric displacement of a saline solution and using a Methane Tube. Methane concentration in the biogas has been determined using an automatic gas analyzer and an Agilent 7890B gas chromatograph.*

***Results.*** *The physicochemical characteristics of native and concentrated vinasse, sweet sorghum bagasse, and digestate as substrates for biogas production have been determined. The combined use of beet vinasse and sweet sorghum bagasse has been shown to increase the abundance of active methanogenic microflora in the bioreactor and to enhance overall process productivity.*

***Conclusions.*** *A process flow diagram for the production of biogas and organic fertilizers from vinasse and lignocellulosic biomass has been developed, taking into account the current technical and economic conditions of Ukrainian enterprises. The proposed technology demonstrates strong practical potential and can be implemented in alcohol, bioethanol, and sugar production industries.*

*Keywords: biogas, anaerobic fermentation, bioethanol production waste, distiller's grains, beet vinasse, sweet sorghum bagasse, digestate.*

The development of the energy sector has a decisive impact on a country's economic performance and the standard of living of its population [1]. Ukraine is unable to meet its demand for mineral energy resources from domestic sources, as only about 20% of its natural gas and oil consumption is covered by domestic production [2, 3]. A defining feature of Ukraine's contemporary energy sector is its transition toward the development of energy systems based on non-conventional and renewable energy sources. Among these, approaches based on the use of biological systems have proven to be particularly effective and promising. In this context, biological technologies for converting biomass into energy carriers through biomethanogenesis have become relatively well established [4, 5].

Biogas produced from organic feedstocks via biomethanogenesis — resulting from the decomposition of complex organic substrates of various origins by mixed microbial consortia — typically consists of 50—70% methane and 30—50% carbon dioxide, along with trace amounts of hydrogen sulfide, nitrogen, hydrogen, and other impurities [6]. The methane-to-carbon dioxide ratio depends on the nature of the substrate and the pH conditions during the biomethanogenesis process. In addition to addressing energy generation, biomethanogenesis plays a critical environmental role, as it enables the treatment and utilization of waste from agricultural, industrial, and municipal sources, including wastewater and solid waste from urban landfills [5].

In this study, the focus is placed on waste generated by bioethanol production facilities that use beet molasses as a feedstock. The total production capacity of such plants in Ukraine is approximately 70,000 tonnes of bioethanol per year. The treatment and/or utilization of the resulting distillery stillage (vinasse) remains a significant challenge. In Ukraine, vinasse is commonly discharged onto filtration fields, which become sources of surface water and air pollution, particularly during the warm season. This disposal practice not only causes environmental damage but also results in direct economic losses for producers [6]. Over the past decade, intensive research efforts have been undertaken to investigate the anaerobic digestion of vinasse for energy recovery through methane fermentation [7].

Vinasse (molasses stillage) is the liquid residue remaining after the distillation of bioethanol; it is a dark-brown effluent characterized by a high chemical oxygen demand (COD) [8]. Industrial enterprises consistently face significant challenges associated with vinasse disposal (Fig. 1). As a result, they are often compelled to engage with environmental regulatory authorities and local communities and, in some cases, to suspend produc-

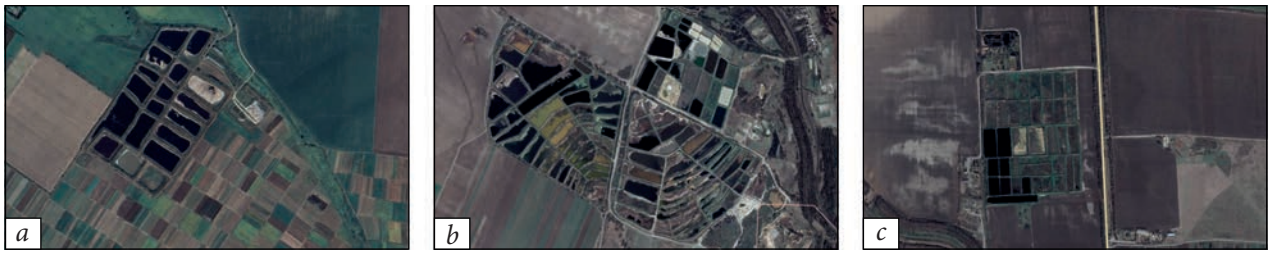


***Fig. 1.*** Satellite images of sugar beet vinasse filtration fields obtained from Google Maps (bar = 100 m): *a* — *West Way* LLC (formerly the Khorostkiv Distillery, Ternopil Oblast); *b* — *SKIF-96* Corporation LLC (formerly the Haisyn Distillery, Vinnytsia Oblast); *c* — *Polyhonal* Agricultural Cooperative (formerly the Trostianets Distillery, Vinnytsia Oblast)

tion operations periodically due to the adverse environmental impacts of vinasse accumulation.

At the same time, vinasse contains residual proteins and carbohydrates, as well as significant amounts of glycerol, betaine, and other organic compounds. The use of vinasse for anaerobic (methane) fermentation requires the addition of a co-substrate due to its low C/N ratio, insufficient concentrations of macro- and microelements, high contents of potassium salts and sulfates, and the presence of phenolic compounds that inhibit methanogenesis [9]. One approach to addressing these limitations is the incorporation of lignocellulosic biomass as a co-substrate.

In parallel, large quantities of agricultural residues, particularly straw, remain underutilized or are burned directly in the fields, thereby generating additional $CO_2$ emissions. This biomass can instead be efficiently utilized for biogas production. The baseline potential of residual biomass in Ukraine amounts to approximately 2.13 million tonnes of conventional fuel equivalent (with a calorific value of 29.3 MJ/kg). When agricultural by-products such as straw and vinasse are used, it becomes possible to generate nearly twice as much energy in addition to the primary product. Specifically, alongside bioethanol with an energy potential of 22.56 MWh · ha$^{-1}$ · year$^{-1}$, an additional 45.06 MWh · ha$^{-1}$ · year$^{-1}$ can be obtained from by-products [10].

For these reasons, the aim of this study was to develop a technology for the integrated processing of plant-based energy feedstocks (beet molasses and sweet sorghum biomass) into energy carriers (fuel ethanol and biogas) and organic fertilizers, with the objective of enhancing Ukraine's energy independence and environmental security. The present research has focused on the needs of Ukrainian bioethanol plants and on the development of a biotechnology for vinasse utilization in biogas reactors through the immobilization of methanogenic microorganisms on a lignocellulosic substrate.

The vinasse used in the study was supplied by the State Enterprise *Haisyn Distillery* (Haisyn, Vinnytsia Oblast, Ukraine). It was produced during February–March and stored in a freezer at a temperature of −16 ± 2 °C. Prior to the experiments, the vinasse was thawed at room temperature for 2—3 hours. Concentrated vinasse was also used in the study; concentration was carried out using a rotary evaporator until a dry matter content of 40—60% was achieved.

Sweet sorghum was cultivated in the Shostka district of the Sumy Oblast, within the Polissia zone. Laboratory experiments employed both ground and chopped sorghum bagasse (Fig. 2). For the pilot-scale experimental installation, sorghum bagasse particles with lengths ranging from 2 to 8 cm were used.

Cattle manure was added as a nutrient medium serving as a source of microorganisms essential for the anaerobic methanogenesis process, to optimize the C/N ratio when using sugar beet vinasse for biogas production, and to accelerate and enhance the completeness of methane fermentation [11].

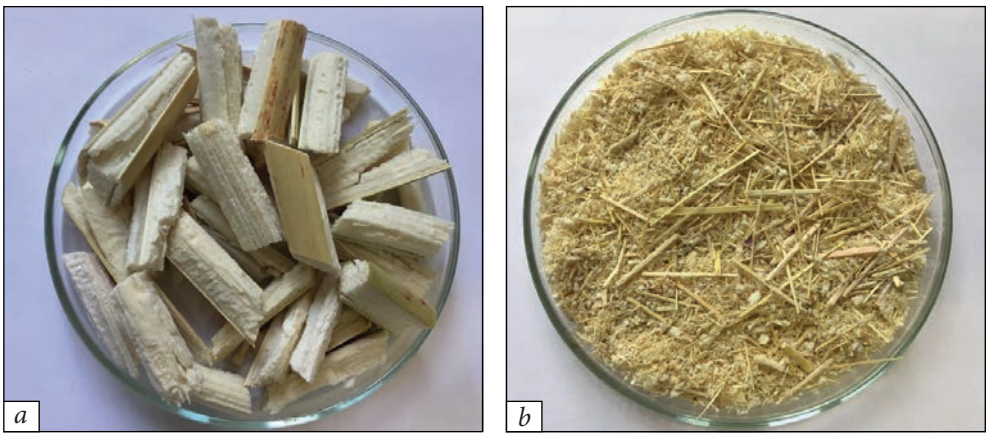


***Fig. 2.*** Sweet sorghum bagasse: *a* — chopped into 2.5—3 cm long pieces approximately; *b* — finely ground

Moisture content was determined gravimetrically by drying samples in a drying oven at 105 °C to constant weight, following standard procedures. The dry matter (DM) content was calculated by subtracting the moisture content from 100%. Ash content of the dry residue was determined by combustion in a muffle furnace at 550 °C to constant weight using a standard method. The organic matter content (OM), a critical parameter for anaerobic digestion, was calculated using the following equation:

$$\text{OM (\%)} = 100\% - \text{moisture content (\%)} - \text{ash content (\%)}.$$

Total nitrogen (N) was determined using the Kjeldahl method in accordance with DSTU ISO 1871:2003. The microelement composition was analyzed using an inductively coupled plasma optical emission spectrometer (ICP-OES, Agilent Atomic Spectroscopy 5110). Sulfate content was determined by a complexometric method.

The volume of biogas produced was measured by volumetric displacement of a saline solution in laboratory experiments, or using Methane Tube devices (https://www.methantube.com, Italy) under industrial conditions. The methane content of the biogas was determined using an automatic gas analyzer in laboratory studies and by gas chromatography (Agilent 7890B GC System, USA) under industrial conditions.

To model the main types of methane fermentation technologies (continuous, semi-continuous, and batch processes), experimental setups of different scales were employed. All laboratory studies on methane fermentation were conducted in biochemical reactors under mesophilic conditions (35 ± 5 °C) with periodic substrate loading.

Several reactor designs were used, differing in volume, heating method, and mixing system; however, the basic configuration of the installations was identical. In general, the biogas system consisted of a methanogenesis bioreactor (a flask placed on a heated magnetic stirrer and equipped with a thermometer), a biogas collection vessel operating by water displacement, and a water receiving vessel.

The water (or solution) level in the biogas collection vessel was recorded daily. Knowing the vessel volume, calculated as $\pi r^2 h$ (where $r$ is the radius of the vessel and $h$ is the height of the liquid column), the biogas yield was determined in cubic centimeters over the time interval since the previous measurement. By dividing this volume by the elapsed time between two consecutive measurements, the biogas production rate was calculated and expressed in cubic centimeters per hour:

$$\text{Biogas yield} = (V_1 - V_2) / \Delta t,$$

where $V_1$ is the initial volume of water, $V_2$ is the final volume of water, and $\Delta t$ is the time interval between two consecutive measurements.

***Fig. 3.*** *Methane Tube* setup for rapid determination of biogas yield from various substrates. The installation includes a biogas reactor with a working volume of 30 $dm^3$ and is located at the NUBiP

***Fig. 4.*** Pilot-scale biogas installation of *Eco-Energia LLC* with a reactor volume of 2 $m^3$

To model the main anaerobic digestion processes under conditions closer to industrial operation, a *Methane Tube* system (https://www.methantube.com) with a working volume of 6 $dm^3$ was used for the rapid determination of biogas yield. In addition, a pilot-scale unit with a reactor volume of 30 $dm^3$ was employed (Fig. 3). This unit was specifically designed and constructed at the National University of Life and Environmental Sciences of Ukraine (NULES) in collaboration with colleagues for experimental studies of biogas technology.

To optimize the fermentation process under conditions as close as possible to industrial operation, a pilot-scale installation with a reactor volume of 2 $m^3$ was used (Fig. 4). The biogas unit was installed at *Eco-Energia* LLC (Sumy Oblast, Ukraine). This installation has enabled simulation of the hydrodynamic regime of an industrial reactor, as well as control of the mixing intensity and the retention of methanogenic biomass immobilized on a carrier.

The pilot-scale unit was constructed according to our calculations and engineering drawings by specialists of *Eco-Energia* LLC specifically for scaling up and validating the technology under industrial conditions.

It is precisely through the optimization of the anaerobic digestion technology for vinasse co-fermented with sorghum bagasse on this pilot-scale biogas installation that a set of practical recommendations has been formulated for the implementation of the proposed methane fermentation technology for vinasse. Based on these results, a process flow diagram has been developed, which can be recommended to bioethanol plants in Ukraine for the environmentally safe utilization of their production waste.

In accordance with the stated objective, the research has been structured as follows:

1. Determination of the physicochemical composition of bioethanol production waste (vinasse) in order to identify factors that hinder its use in biogas reactors, followed by the proposal of measures to eliminate or mitigate these limiting factors.

2. Experimental investigation of methane fermentation of biological feedstocks (vinasse and bagasse from sweet sorghum stalks) and identification of the key parameters influencing the processes of their joint biotransformation.

3. Establishment of the optimal component ratio of the composite substrate to achieve maximum bioconversion depth and biogas yield.

4. Determination of optimal process control parameters based on the composition and concentration of volatile fatty acids (VFAs) in the fermentation medium, as well as selection of optimal particle sizes of the lignocellulosic substrate used as a carrier for the methanogenic microbial consortium.

5. Generalization of the experimental results and development of technological recommendations for organizing the bioconversion of the composite substrate into biogas under industrial conditions.

Composition of feedstocks for biogas production. The average characteristics of vinasse, sweet sorghum bagasse, and cattle manure (CM) obtained from laboratory analyses are summarized in Table 1.

As reported in the literature [11, 14], fermentation of a single substrate, such as vinasse, is feasible; however, the co-fermentation of vinasse with cattle manure or sweet sorghum bagasse significantly increases biogas yield compared with the use of any individual substrate. This finding has been confirmed by our experiments. A critical parameter in fermentation is the carbon-to-nitrogen (C/N) ratio. Vinasse contains a relatively high total nitrogen content (7.8—9.0% on a dry matter basis, according to our analyses), which can inhibit methanogenic bacteria. In contrast, sweet sorghum bagasse contains approximately three times less nitrogen (1.3—2.5% on a dry matter basis) and a higher content of organic matter, particularly carbon. To achieve an optimal C/N ratio of 25—35 in the feedstock for biogas production, co-substrates such as cattle manure and sweet sorghum bagasse were added. The combined use of these substrates ensures a more balanced C/N ratio during the anaerobic fermentation of vinasse [12].

Unlike molasses vinasse, sweet sorghum bagasse is a relatively dry substrate (Table 1). This characteristic helps retain microbial biomass in the methanogenic reactor, preventing washout and increasing the biomass-to-microorganism retention ratio, which is important for the economic efficiency of the process. The integrated use of co-substrates with different proportions of components involved in methanogenesis leads to more complete fermentation and, consequently, a higher yield of the final product — biogas.

*Table 1.* **Chemical Characteristics of Substrates for Anaerobic Fermentation**

| Raw material | Organic dry matter, % | Ash content, % | Moisture content, % |
|---|---|---|---|
| Sorghum bagasse | 90.52 ± 0.09 | 2.67 ± 0.14 | 6.81 ± 0.20 |
| Beet vinasse | 11.60 ± 0.90 | 2.05 ± 0.09 | 86.35 ± 0.90 |
| Cattle manure | 9.03 ± 0.09 | 8.87 ± 0.20 | 82.9 ± 0.90 |

The content of sulfur and its derivatives plays a significant role during anaerobic fermentation. Sulfates are particularly undesirable because, in an anaerobic reactor, they are reduced by sulfate-reducing microorganisms to hydrogen sulfide ($H_2S$). Biogas contaminated with $H_2S$ cannot be used without additional purification [13]. The sulfate content in vinasse was determined using a complexometric method. Laboratory analyses at the Haisyn Distillery have shown a sulfate concentration of 0.36 ± 0.05 g/100 $cm^3$, which is 28% lower than the literature value of 0.5 ± ± 0.05 g/100 $cm^3$ [14].

The high sulfur content in vinasse is caused by the addition of 5—10 kg of sulfuric acid per ton of molasses during ethanol production. This issue can be partially mitigated by using lactic acid instead of sulfuric acid at the production stage to optimize pH. Previous studies conducted by our team [15, 16] have demonstrated that sulfur content can also be reduced through evaporation (concentration). Although this process increases the concentration of vinasse, it facilitates the separation of inhibitory sulfur compounds. Concentrating vinasse, thereby increasing the organic matter content in the substrate, can enhance fermentation efficiency and reduce reactor volume, which is economically advantageous for production facilities. Additionally, concentrated vinasse can be co-fired in industrial boilers with natural gas to provide energy self-sufficiency for bioethanol production [17].

The productivity of anaerobic fermentation can also be regulated through the addition of macro- and microelements. Research has shown that microelements significantly influence biomass conversion to biogas. Essential metals that enhance methane production in methanogenic microorganisms include iron, cobalt, molybdenum, selenium, calcium, magnesium, zinc, copper, manganese, tungsten, and boron. While these elements are crucial for methanogenesis, their environmental impact, particularly in the case of heavy metals, must be carefully managed [18].

An analysis of macro- and microelements was conducted in potential substrates for biogas production: sugar beet vinasse and sweet sorghum bagasse. The microelement composition of vinasse and sorghum bagasse was determined using atomic absorption spectrometry. Vinasse was found to be deficient in macroelements such as calcium and magnesium, indicating a limited potential for achieving high methane yields when vinasse is used as a mono-substrate for anaerobic fermentation. On a positive note, vinasse did not contain the heavy metal lead, and other heavy metals were present only in trace amounts.

In contrast, sorghum bagasse exhibited relatively high calcium content, suggesting good potential for methane production, and similar trends were observed for magnesium. Manganese was present in small quantities, which can support anaerobic fermentation. Importantly, cadmium and lead concentrations were very low, indicating that the soil in which the sweet sorghum was cultivated was not contaminated with heavy metals. This also suggests that the digestate obtained after fermentation can be safely used as an organic fertilizer.

Methane fermentation experiments were conducted under laboratory conditions in five experimental series to evaluate substrate ratios, processing methods, and key process parameters. All experiments were carried out in triplicate. Anaerobic fermentation was performed in a laboratory-scale reactor under mesophilic conditions (37 °C) with periodic substrate loading. The results of one experimental series are presented in Fig. 5.

The laboratory experiments have allowed comparison of different operational modes and stages, including fermentation temperature, substrate volume, fermentation duration, mixing method, composition of the liquid in the biogas collection vessel, and processing of lignocellulosic biomass. It is important to note that all these parameters significantly influence biogas yield. Based on data obtained from the laboratory experimental series, it has been demonstrated that the addition of lignocellulosic biomass to vinasse as

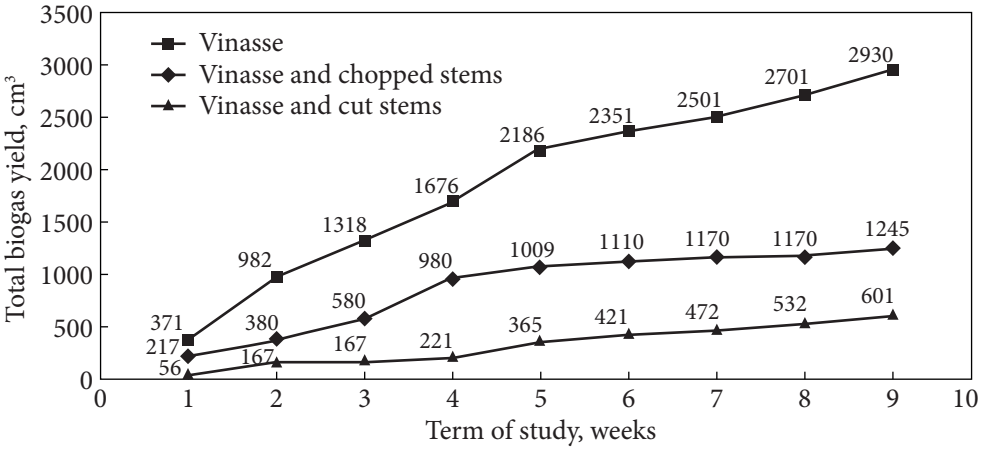


***Fig. 5.*** Methane fermentation of vinasse as a monosubstrate and in co-digestion with lignocellulosic biomass under laboratory conditions

a substrate for methane fermentation increases biogas production.

However, the degree of biomass comminution is critical. In laboratory-scale experiments, larger pieces of bagasse formed a surface crust that did not undergo fermentation and impeded biogas release. The highest biogas yield was observed when the substrate consisted of vinasse supplemented with finely milled sweet sorghum bagasse at a ratio of 5% dry matter of bagasse to the volume of vinasse, as illustrated in the corresponding graph. Adding larger amounts of bagasse increased substrate viscosity, which hindered mixing and reduced fermentation efficiency.

The primary objective of this research was to develop an anaerobic fermentation technology for vinasse under industrial conditions, enabling recommendations for implementation at bioethanol and sugar production facilities. A series of experiments was performed using a pilot-scale biogas installation at the bioethanol plant of *Eco-Energia* LLC in an anaerobic reactor with a volume of 2 m³. This reactor allowed determining the optimal particle size of the lignocellulosic carrier for methanogenic microorganisms and fermentation parameters closely resembling industrial conditions.

The biogas installation consisted of a methanogenesis reactor, a digestate collection tank, and a gas holder for biogas storage. The reactor operated in continuous mode for 26 days in each experiment. Substrate loading and digestate removal occurred once daily, while mixing was maintained continuously using a screw pump. The experimental results for determining the optimal particle size of bagasse, serving as both a carrier for immobilized methanogens and a co-substrate for vinasse, are presented in Table 2.

*Table 2.* **Determination of the Optimal Particle Size of Bagasse**

| Term of fermentation, days | Bagasse particle length, cm | Biogas yield, m³/kg DM | Loading, kg DM/m³· day | Inoculum | Substrate |
|---|---|---|---|---|---|
| 26 | 1—2 | 0.42 ± 0.12 | 2.4 | Cattle manure | Vinasse + bagasse |
| 26 | 2—5 | 0.75 ± 0.28 | 2.4 | Cattle manure | Vinasse + bagasse |
| 26 | 5—10 | 0.36 ± 0.07 | 2.4 | Cattle manure | Vinasse + bagasse |

*Note:* 1.5 m³ native vinasse + 8 kg bagasse Moisture content 18%; 5 kg cattle manure.

Anaerobic degradation of organic matter during methanogenesis occurs as a multi-stage process requiring the coordinated activity of at least three groups of microorganisms: hydrolytic bacteria, acidogens, and methanogens [7, 15]. Two factors critically influence the course of fermentation:

1. The hydrolysis rate is several times higher than the methanogenesis rate, which also affects the growth rate of active biomass.

2. Methanogens are easily washed out from the reactor because gas bubbles forming on the surface of cells carry them to the liquid surface and out of the reactor.

The presence of lignocellulosic particles in the reactor helps retain anaerobic microorganisms on their surfaces [2, 4]. The rate of microbial cellulose decomposition depends on the specific surface area of the particles, which in turn depends on their geometric size. Laboratory experiments have shown that smaller, finely milled bagasse particles increase the rate of the process. However, in industrial-scale reactors, excessive comminution leads to the washout of fine particles, which serve as carriers for methanogens, reducing their concentration in the reactor and slowing the methanogenesis process. Based on experiments in the pilot-scale installation, the optimal particle size range of the lignocellulosic co-substrate, at which methanogenesis proceeds most intensively, is 2—5 cm.

A key goal in biogas production is to retain the maximum number of methanogens in the reactor. In addition to measures for biomass retention, it is essential to prevent excessive accumulation of VFAs during hydrolysis [12, 14]. Excessive VFAs inhibit methanogens and can even completely halt the process, leading to "conservation" of the reactor content, accumulation of mainly butyric, propionic, and acetic acids, acidification of the mixture, pH reduction, and cessation of methanogenesis. Table 3 presents the results of VFA monitoring during the continuous fermentation of pure vinasse.

As the substrate loading on the reactor increased to 3.5 kg of dry matter per cubic meter of reactor per day, the concentration of VFAs rose rapidly to critical levels. By day 12, even without further increasing the load, acidification occurred, leading to "conservation" and complete cessation of fermentation and methanogenesis.

For comparison, experiments were conducted using a different substrate: vinasse supplemented with 10% (dry matter basis) sweet sorghum biomass relative to the mass of vinasse (Table 4). The results indicate that when vinasse is co-fermented with this co-substrate, the reactor reaches a critical state at a higher loading rate — 4.5 kg of dry matter per cubic meter of reactor per day.

*Table 3.* **Monitoring of Volatile Fatty Acids (VFAs) During Continuous Fermentation of Pure Vinasse**

| VFA | Units | Fermentation period, days / Loading, kg /m³ · day | | | | |
|---|---|---|---|---|---|---|
| | | 2—4/ 2.0 | 4—6/ 2.5 | 6—8/ 3.0 | 8—10/ 3.5 | 10—12/ 3.5 |
| Acetic acid | g/dm³ | 2.71 ± 0.23 | 4.32 ± 0.23 | 3.82 ± 0.23 | 3.66 ± 0.75 | 4.63 ± 0.81 |
| Propionic acid | g/dm³ | 0.85 ± 0.22 | 1.68 ± 0.29 | 2.30 ± 0.28 | 2.79 ± 0.46 | 2.91 ± 0.65 |
| Isobutyric acid | g/dm³ | 0.01 ± 0.01 | 0.12 ± 0.06 | 0.11 ± 0.21 | 0.20 ± 0.15 | 0.22 ± 0.16 |
| Butyric acid | g/dm³ | 0.03 ± 0.01 | 0.23 ± 0.16 | 0.20 ± 0.01 | 0.20 ± 0.11 | 0.12 ± 0.14 |
| Isovaleric acid | g/dm³ | 0.01 ± 0.02 | — | 0.07 ± 0.01 | 0.17 ± 0.13 | 0.12 ± 0.03 |
| Valeric acid | g/dm³ | — | 0.02± 0.01 | 0.02 ± 0.01 | — | — |
| Total VFAs (titr.) | g/dm³ | 3.92± 0.70 | 5.7 ± 2.22 | 5.98 ± 1.35 | 6.7 ± 3.22 | **8.76 ± 2.23 Conservation!** |

Based on the methanogenesis experiments and monitoring of VFA concentrations, several preliminary conclusions have been drawn:

- To prevent "conservation" of the process, the maximum total VFA concentration in the reactor should not exceed 6 g/L.
- Vinasse fermentation for biogas production is most effective when 5—15% (depending on reactor size and the need to retain methanogens) of lignocellulosic biomass, such as sweet sorghum stems, is added.
- The particle size of the lignocellulosic biomass should be optimized to maximize the retention of methanogenic microorganisms within the working volume of the reactor.

After anaerobic fermentation in the biogas reactor and the production of the primary methanogenesis product — biogas, a mixture of methane, carbon dioxide, and minor volatile compounds — a liquid residue, known as digestate, remains. Digestate can be used to enrich soils as an organic fertilizer [19]. The methanogenesis technology enables the conversion of virtually any organic material into a potential energy source (biogas or biomethane) while simultaneously producing a nutrient-rich organic fertilizer, supporting zero-waste production and nutrient cycling.

Digestate contains a substantial amount of nutrients and does not pollute the environment, as it is free from fermentation byproducts. In biogas production, digestate represents a valuable fertilizer with high levels of nutrients and humus. Its key properties [19] include:

- Organic carbon content, particularly in the form of humic substances (1—3% by mass);
- A complex of essential macro- and microelements for plant growth (N, P, K, Mg, S);
- Enhancement of crop yields as compared with conventional mineral fertilizers;
- High availability of nitrogen for plants (10—70% as compared with unfermented material);
- Optimal soil pH range of 6.8—7.5;
- Active bacterial populations that facilitate the decomposition of organic matter in the soil;
- Moisture content that supports nutrient penetration into soil, reduces bulk density, and improves water retention;
- Potential reduction in greenhouse gas emissions (up to 6 kg $CO_2$ per 1 kg of replaced nitrogen fertilizers).

In this study, digestate obtained from laboratory-scale methanogenesis experiments was investigated, along with digestate from operating biogas plants in Ukraine. The digestate produced during laboratory methanogenesis experiments exhibited a neutral to slightly acidic pH. The redox potential was predominantly reducing; however, in samples where methanogenesis was more complete, the potential shifted to oxidizing or transitional redox states. Table 5 presents the main characteristics of digestate produced in the biogas reactor at the experimental facility of *Eco-Energia* LLC (Sumy Oblast).

*Table 4.* **Monitoring of Volatile Fatty Acids (VFAs) During Continuous Fermentation of Vinasse with 10% Sweet Sorghum Biomass**

| VFA | Units | Fermentation period, days / Loading, kg /m³ · day | | | | |
|---|---|---|---|---|---|---|
| | | 2—4/ 2.0 | 4—6/ 2.5 | 6—8/ 3.5 | 8—10/ 4.0 | 10—12/ 4.5 |
| Acetic acid | g/dm³ | 2.12 ± 0.34 | 2.96 ± 0.13 | 3.71 ± 0.22 | 3.15 ± 0.64 | 4.22 ± 0.27 |
| Propionic acid | g/dm³ | 0.65 ± 0.14 | 0.94 ± 0.35 | 2.16 ± 0.17 | 2.01 ± 0.36 | 2.12 ± 0.33 |
| Total VFAs (titr.) | g/dm³ | 3.6 ± 0.11 | 3.18 ± 0.64 | 4.78 ± 0.33 | 5.56 ± 0.65 | **7.76 ± 0.89 Conservation!** |

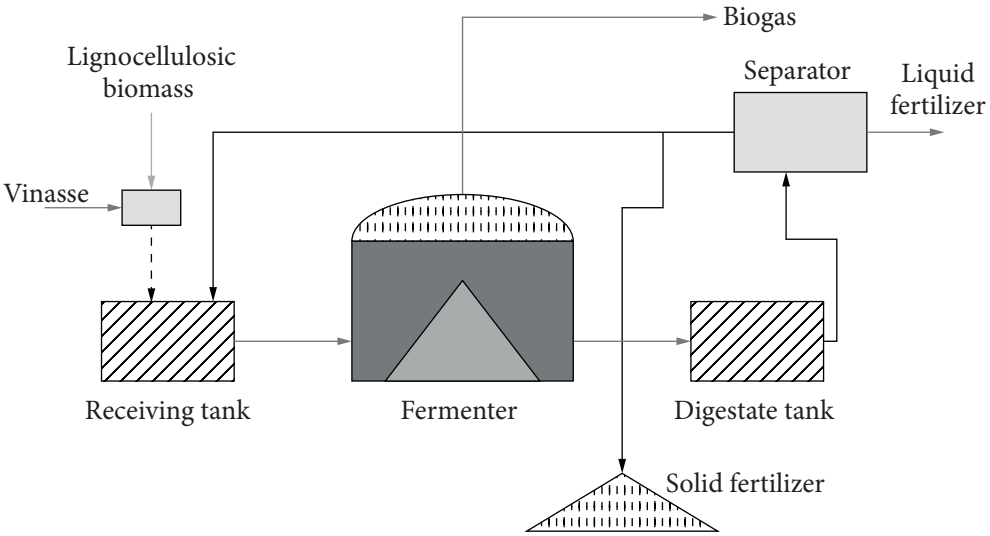


***Fig. 6.*** Schematic diagram of a biogas plant for the utilization of vinasse with lignocellulosic biomass

As can be seen from the results, the digestate contains a high proportion of organic matter, with the majority of nitrogen present as ammonium nitrogen, which is readily assimilated by plants. It exhibits low levels of volatile fatty acids and a pH optimal for soil application. The findings indicate that digestate produced after biogas generation retains all essential nutrients for plants, has a neutral pH, contains no fermentation byproducts, and can therefore be used as an effective organic fertilizer.

These results have provided the foundation for developing a technology for the integrated conversion of plant-based energy substrates — namely, beet vinasse and sweet sorghum biomass — into energy carriers (biogas) and organic fertilizers. A conceptual process flowchart for the production of biogas and organic fertilizers from vinasse (beet stillage) and lignocellulosic biomass has been proposed, taking into account current technical and economic requirements of Ukrainian enterprises. The schematic representation of the

*Table 5.* **Parameters of Digestate Obtained from the Biogas Reactor at the *Eco-Energia* Pilot Installation (Sumy Oblast, Ukraine)**

| Parameter | Units | Digestate after methanogenic fermentation |
|---|---|---|
| Dry matter | g/kg | 46.4 ± 0.5 |
| Organic matter | g/kg | 24.8 ± 0.1 |
| Ammonium nitrogen | g/dm$^3$ | 2.76 ± 0.04 |
| Total nitrogen | g/dm$^3$ | 3.56 ± 0.07 |
| Protein | % DM | 20.2 ± 0.1 |
| Carbon (C) | g/dm$^3$ | 12.44 ± 0.09 |
| Total VFA | g/dm$^3$ | 4.89 ± 0.08 |
| pH | — | 7.97 |
| COD (Chemical Oxygen Demand) | g $O_2$/dm$^3$ | 33.16 ± 0.12 |

biogas complex for vinasse utilization with lignocellulosic biomass is shown in Fig. 6.

The proposed scheme has been recommended for detailed development during the design of biogas complexes at enterprises such as the Haisyn Distillery, the Trostianets Distillery, and *Eco-Energia* LLC. Partial recirculation of lignocellulosic biomass into the reactor facilitates the retention and accumulation of methanogens. Thus, the anaerobic process in the reactor achieves a triple objective:

- neutralizing harmful compounds in vinasse and converting it into a liquid fertilizer;
- producing an alternative fuel — biogas;
- obtaining an organic fertilizer.

Based on the results of this study and the conclusions drawn, specific practical recommendations have been formulated for Ukrainian enterprises to organize the bioconversion of bioethanol production residues under industrial conditions:

1. Substrate composition: Fermentation of vinasse for biogas production should be carried out with the addition of 5—15% lignocellulosic biomass, depending on reactor size and the need to retain methanogens, particularly sweet sorghum stems.

2. Particle size of the lignocellulosic biomass: The size of biomass particles should correspond to the conditions that maximize the accumulation of methanogenic microorganisms within the reactor volume. For industrial reactors, the optimal particle size of the carrier — sweet sorghum bagasse — is 2—5 cm. This ensures adequate hydrolysis of the carrier, maintains the necessary C/N ratio in the fermentation medium, and achieves an optimal concentration of methanogenic biomass for stable fermentation.

3. VFA control: To prevent process "conservation" or inhibition, the maximum total concentration of VFAs in the reactor should not exceed 6 g/L. Process monitoring should also include the acetate-to-propionate ratio, which should remain ≥1.5, as lower ratios may inhibit methanogenesis.

4. Recirculation of lignocellulosic residues: Non-hydrolyzed lignocellulosic biomass should be separated from the digestate and returned to the reactor along with immobilized anaerobic biomass to increase methanogen concentration.

Under these parameters — including the quantity and particle size of the carrier, VFA concentration, and acetate-to-propionate ratio — the substrate loading based on dry matter can reach up to 4 kg/m³ per day.

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# РОЗРОБЛЕННЯ ТЕХНОЛОГІЇ ОТРИМАННЯ БІОГАЗУ ТА ОРГАНІЧНИХ ДОБРИВ ІЗ ВІДХОДІВ ВИРОБНИЦТВА БІОЕТАНОЛУ

**Вступ.** Одним із шляхів доповнення та заміни природного газу є біогаз. Його отримують з органічної сировини при біометаногенезі, він аналогічний природному газу.

**Проблематика.** Виробництво 1 м$^3$ біоетанолу супроводжується утворенням 10—15 м$^3$ вінаси, відходу, що скидається на поля фільтрації. Її можна використовувати як сировину для отримання біогазу, що дає біоетанольним заводам енергонезалежність. Витрати на створення біогазових установок окуповуються через отримання енергії та уникнення штрафних санкцій за забруднення довкілля.

**Мета.** Розробити біотехнологію використання вінаси та лігноцелюлозного ко-субстрату для отримання біогазу та органічних добрив на підприємствах біоетанолу, щоб вирішити проблеми альтернативних енергоносіїв біоетанольних заводів України й утилізації відходів.

**Матеріали й методи.** Визначали вологість висушуванням при 105 °С, зольність — спалюванням при 550 °С, нітроген — методом К'єльдаля, сірку — комплексометричним методом, мікроелементний склад — атомно-абсорбційною спектрометрією. Досліджували сировину для біогазу: вінасу, багасу сорго, а також дигестат. Метанове ферментування вивчали у мезофільних умовах, при періодичному завантажуванні. Кількість біогазу визначали об'ємним витісненням соляного розчину та у *Methane Tube*, а вміст метану в біогазі — автоматичним газоаналізатором та газовим хроматографом *Aglient 7890B GC System*.

**Результати.** Визначено фізико-хімічні показники нативної та концентрованої вінаси, багаси цукрового сорго, дигестату як сировини для отримання біогазу. Спільне використання бурякової вінаси та багаси цукрового сорго призводить до збільшення кількості активної метаногенної мікрофлори в реакторі й підвищує продуктивність процесу.

**Висновки.** Створено технологічну схему виробництва біогазу та органічних добрив з вінаси та лігноцелюлозної біомаси з урахуванням сучасних техніко-економічних вимог підприємств України. Технологія є перспективною і може бути застосована на спиртових, біоетанольних та цукрових виробництвах.

*Ключові слова:* біогаз, анаеробне ферментування, відходи виробництва біоетанолу, післяспиртова барда, бурякова вінаса, багаса цукрового сорго, дигестат.