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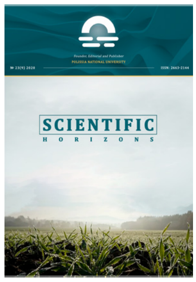

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Energy and Ecological Prerequisites for the Choice of Technologies for Processing Organic Livestock Waste

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Abstract. For modern Ukraine and European countries, the issues of soil restoration after intensive cultivation and reducing the cost of agricultural products by including energy from alternative sources in the energy supply of technological processes are relevant. Therefore, considerable attention is paid to the development of biogas technologies and the production of organic waste. The purpose of the study is to improve the efficiency of the manure processing system with subsequent production of biogas and compost by consistently implementing anaerobic and aerobic fermentation technologies. Economically feasible ways of using organic animal waste are presented. It is proved that the introduction of biogas technologies is economically feasible only in the conditions of functioning of closed systems for the production of crop and livestock products. The most effective combination was the consistent implementation of anaerobic digestion technology and accelerated biothermal composting. Anaerobic methane fermentation, in contrast to the process of composting bio-raw materials, allows more than 55% of carbon to be disposed of in the form of high-calorie methane gas, due to which nitrogen losses are reduced from 20-25% to 1.5-3%. Analytical studies show that as a result of processing 1 tonne of cattle manure, 23.22 g^3 of biogas with an energy equivalent of 510 MJ can be obtained. It is also shown that by making changes made by accelerated biothermal composting energy costs for the production of an equivalent (according to NPK) amount of mineral fertilisers are reduced by 895 MJ. However, it should be borne in mind that in the conditions of construction and maintenance of a biogas system, the high start-up and operating costs leads to the use of accelerated biothermal composting technology at the first stage of processing bio-raw materials. The results obtained can be used as the basis for a modern methodology for calculating the expediency of application of a particular technology depending on the operating conditions of the agricultural enterprise and the technological task regarding the volume of production of finished products. This would allow determining the rational parameters of the bioenergy system and increase the energy and ecological efficiency of biogas and high-quality compost production processes from organic raw materials

Keywords: anaerobic methane fermenztation, accelerated biothermal composting, bioenergy conversion, organic raw materials

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INTRODUCTION

The agro-industrial sector is one of the most important links in the economic system of most countries of the world with a market economy (Grechko *et al*., 2020). The production of agricultural products is associated with the buildup of a significant amount of organic raw materials, the useful disposal of which is not given enough attention (Shevchenko & Lyashenko, 2012). The European legislative framework provides for a number of regulatory documents on waste management, the basic of which are the Nitrates Directive (Council Directive 91/676/EEC, 1991) and the Industrial Emissions Directive (Directive 2010/75/EU, 2010). These documents provide for: the implementation of a comprehensive assessment of the negative impact on the environment with the identification of affected areas; environmental monitoring; the use of highly effective available technologies; prevention measures and an action plan to minimise risks at both local and national levels. This approach reduces environmental risks and promotes the development of technologies for further processing of waste, including biological ones. Modern Ukraine, which is integrating into the European Economic Area, is adapting its regulatory framework to the European one, including in the context of bio-waste management.

A powerful source of bio-waste from the agro-industrial sector in the vast majority of countries of the world is animal husbandry, partly – pig and poultry farming (Yoshizaki *et al*., 2013). In these industries, organic raw materials such as milk, meat, and eggs are a commodity – organic fertiliser, which, unfortunately, is almost not applied to the soil to maintain its fertility (Shevchenko *et al*., 2009). In Ukraine, of all types of bio-waste, cattle manure is the most prevalent, which can be used both for the production of energy (biogas) and bio-fertilisers (Shevchenko *et al*., 2011). In Ukraine, in contrast to the EU countries, where small and medium-sized farms with a focus on organic production are developing, more than 50% of livestock farms are industrial facilities with significant volumes of bio-waste. In animal husbandry, about 100 million tonnes of manure is accumulated, in crop production – more than 50 million tonnes of biomass, with manure accounting for more than 60%.

Singapore researchers (Deng *et al*., 2020) note that a promising method of processing bio-waste is the production of biogas, which contains 60-75% CH4 with a calorific value of 20-25 MJ/m^3. In particular, biogas plants are capable of processing manure of pigs and cows, poultry droppings, plant waste, sewage sludge, waste from animal slaughtering shops, etc. The most effective bioreactors are the BRK-100 cassette type of cyclic action with an average daily biogas capacity of 1.5-2 m^3 with 1 m^3 of bioreactor working volume. Biogas production waste mixed with plant biomass is a raw material for fertiliser preparation.

According to Kudria *et al*., 2020), although Ukraine has rich scientific and production potential, unfortunately, it has not been implemented. In Ukraine, the first experimental biogas plant was built in 1954 and successfully operated on the premises of the CNIPTIMET experimental farm (Khortytsia Island, Zaporizhzhia) (Shevchenko *et al*., 2009). In the 1970s, teams of researchers from DEIAMC, ILM NAAS (Zaporizhzhia), UkrNDIagroproekt, UkrCTM and others designed and put into operation bio-installations on the basis of the poultry farm “Kyivska”, in the state farm “rosiya”, Zolotonosha district, Cherkasy Oblast, in the Doslidnytske village of the Kyiv Oblast (Shevchenko *et al*., 2011). In 2003, at the pig farm of the Agro-Oven company in the Olenivka village, Magdalynivskyi district, Dnipropetrovsk Oblast, within the framework of the Dutch government's technical assistance project to Ukraine with the participation of the Dutch company BTG Netherlands, STC Biomasa (Kyiv) and UkrNDIagroproekt (Kyiv), a large biogas plant for processing manure effluents from 15 thousand pigs was put into operation (Shevchenko & Lyashko, 2012). The plant's biogas capacity reached 3,300 m^3/day. Capital investments in the project amounted to about USD 400 thousand with a payback period of more than 10 years. However, the construction and operation of biogas plants in Ukraine and in European countries require significant investment, which, at least partially, should be covered by appropriate state or regional programmes.

For the purpose of partial self-sufficiency of biogas projects, the researchers (Ning *et al*., 2021) propose to combine the production of biogas and biofertilisers. As part of the study, biogas production residues were sequentially processed by thermophilic composting and vermicomposting. This combination allowed eliminating heavy metal inclusions and producing high-quality organic fertilisers in accordance with existing requirements for microbiological indicators. The disadvantage of the proposed solution is the duration of production of biofertilisers, which was 37 days. Reducing the duration of fertiliser production would increase the efficiency of this process and increase the volume of processed raw materials.

Researchers (Meng *et al*., 2020) also sought to investigate the feasibility of using full-scale composting based on biogas fermentation residues. The use of *Anaerolineaceae* and *Limnochordaceae* bacteria and Chaetomium fungi reduced the duration of the process to 30 days. The resulting compost had the following composition as a percentage of absolutely dry matter: nitrogen $N_{tota}l$=2.04%; P_2O_5=1.89%; K_2O=1.68%; S_{total}= 21.88%; ash content – 14.8%; humidity – 57%. The humidity of the original substrate was 61%.

Bai *et al.* (2020) investigated the effect of different proportions of cattle manure and biogas production residues on the degree of degradation of lignocelluloses and humification during composting. An increase in the content of cattle manure extended the duration of the thermophilic phase of the process, contributing to the degradation of organic matter in the substrate and increasing the degree of humification during composting. Depending on the content of cattle manure in the substrate, the cellulose content in the finished compost was 3.9-22.81% less than the cellulose content in the compost from the base substrate (waste from biogas production). Moreover, the addition of cattle manure to the base substrate increased the content of humic acids by 17.21-26.02%. The decision to add 6.7% of cattle manure to the original substrate was optimal in terms of compost quality. The study also raises the question of determining the priority for each farm (region, state) – energy production or restoration of the humus layer of the soil.

Chadwick *et al*. (2015) present solutions to research, infrastructure, socio-economic, and communication problems to ensure the integration of animal husbandry bio-waste into the restoration of soil fertility at the level of fields, farms, regions, etc. This is necessary to protect the environment, reduce the need for the production and use of inorganic fertilisers, and increase farmers' incomes. Practical solutions for the efficient processing of cattle manure in the practice of Chinese enterprises are also presented. The existing barriers to the introduction of green technologies are evaluated, future challenges for rational waste management in this industry are outlined, and the role of the state in this issue is indicated.

The degradation of arable land in Ukraine and the growing energy needs of industry and the population pose a challenge to society to find the best ways to solve these problems. Therefore, the issue of finding engineering and technological solutions for the introduction of various technologies, calculating the economic efficiency of the proposed solutions, and the ability to meet both environmental (recycling of agricultural waste with fertiliser production) and energy (production of heat and electric energy) needs simultaneously remains relevant.

Therefore, *the purpose of the study* is to increase the efficiency of the manure processing system with the subsequent production of biogas and compost by consistently implementing anaerobic and aerobic fermentation technologies.

Object of study – cattle manure processing systems.

Subject of study – interrelation of the sequence of operations for processing cattle manure and the energy and ecological efficiency of such systems.

Hypothesis – the use of aerobic fermentation (composting) after anaerobic digestion would increase the energy and ecological efficiency of the cattle manure processing system.

To achieve this goal, it is necessary to solve the following tasks: 1) analyse closed systems for the production of crop and livestock products; 2) determine the shares of organic livestock waste that should be used for the production of fertilisers and energy; 3) establish the energy and ecological efficiency of the cattle manure processing system with simultaneous production of biogas and compost.

MATERIALS AND METHODS

Methods of scientific search, analysis and synthesis, comparison, statistical methods of analysis and forecasting were used to solve the tasks set. The block diagram of biomass transformation in a closed cycle is developed on the basis of analysis of data from studies by Ukrainian and foreign researchers. The table of energy potential of biogas in Ukraine was compiled based on statistical data for 2010-2021 on the number of livestock at enterprises of the agricultural sector of Ukraine, the amount of waste from the livestock industry, the physical and chemical characteristics of waste from this industry, etc. (Ukraine in numbers 2021, 2022; Animal husbandry of Ukraine 2020, 2021). Based on these data, a schedule of the annual production of cattle manure in Ukraine was also built. The diagram of anaerobic processing of organic waste with the production of biogas and fertiliser and the scheme of technological aspects of manure processing, depending on its moisture content, compiled based on the authors' own developments and practical data obtained at the experimental farm CNIPTIMET (Khortytsia Island, Zaporizhzhia) and the Agro-Oven enterprise (Olenivka village, Dnipropetrovska Oblast).

The scheme of energy balance of feed costs in the cattle body, considering the mineralisation of its waste, was developed on the basis of data obtained by the authors of this study.

Comparative indicators of anaerobic digestion technology and accelerated biothermal composting technology during cattle manure utilisation are presented on the basis of statistical data of the Agro-Oven enterprise (Olenivka village, Dnipropetrovsk Oblast).

The block diagram of transport costs in the implementation of organic waste disposal technology was developed considering the technical and economic performance indicators of the enterprise Agro-Oven for 2010-2020, analysis of biogas and fertiliser production technologies used at the enterprise, and consumer needs. The needs of consumers for fertilisers and energy were determined by a questionnaire (550 forms).

RESULTS AND DISCUSSION

On June 24, 2022, in Kyiv and July 13, 2022, in Prague (Czech Republic), an agreement was signed on Ukraine's accession to the LIFE Programme to address climate change and environmental issues, including air, soil, and water pollution, biodiversity conservation through demonstration of innovative solutions and methods and capacity building of the actors involved (EU LIFE programme, 2022). In addition, on 03.09.2014, the Cabinet of Ministers of Ukraine has submitted Decree No. 791-r

"On Approval of the Action Plan for the implementation of Directive 2009/28/EC of the European Parliament and of the Council" (2014) developed in accordance with the norms of Directive 2009/28/EC of the European Parliament and of the Council on the promotion of the use of energy produced from alternative sources (2010). According to these documents, Ukraine undertakes to develop technical and technological solutions to replace natural energy sources with alternative ones and reduce the harmful impact on the environment.

However, the question of the feasibility of producing energy (biogas) or restoring the state of soils (production of organic fertilisers) should be considered in the context of each individual enterprise, taking into account the state of its economic activity, location, financial capabilities, etc. To understand the needs of enterprises and find optimal energy, environmental and technological solutions in each individual case, a block diagram of biomass conversion in a closed cycle was developed (Fig. 1).

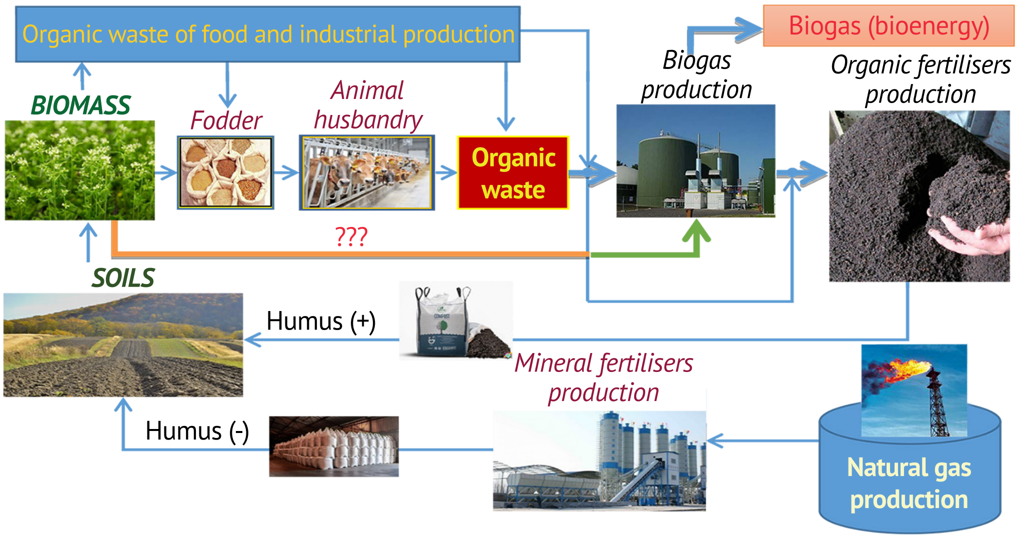

***Figure 1**. Block diagram of biomass conversion in a closed cycle*
***Source:** compiled by the authors*

The diagram includes the production of animal feed from biomass, followed by the production of organic fertilisers and biogas. The conventional technology of producing mineral fertilisers and applying them to the soil is also presented. As an alternative that helps restore the humus layer of soils, it is proposed to replace synthetic fertilisers with organic ones.

According to Kudria *et al.* (2020), despite the fact that animal husbandry in Ukraine is in decline, the total potential for biogas production remains significant and amounts to up to 2 billion m^3/year. However, the lack of a plan for the development of the livestock industry without a certain number of cattle per 100 hectares of arable land (at least 40 animal units) would lead to the loss of fertile soils in Ukraine. An increase in the number of cattle per 100 hectares implies an increase in the yield of organic material (manure), which would contribute to the growth of the potential of biogas production by 2-3 times. If manure is used in a mixture with other organic residues of agricultural production (silage, grass, food waste), the potential for biogas production can increase up to 20 times. Under such conditions, the increase in the technical potential of biogas production would reach 1,790 million m^3/year (1.3 million tonnes of fuel equivalent/year). To understand how much of the conventional energy of Ukraine can be replaced by energy obtained during the utilisation of biogas, Table 1 has been developed based on statistical data for 2010-2021.

***Table 1**. Energy potential of biogas in Ukraine*

Type of biogas	Theoretical potential, mln tonnes of fuel eq.	Coefficient of technical accessibility	Technical potential, mln tonnes of fuel eq.	Energy utilisation rate	Economic potential, mln tonnes of fuel eq.
Biogas from animal husbandry waste	3.27	0.7	2.45	0.3	0.76
Biogas from poultry farming waste	2.69	0.7	2.02	0.3	0.61
Biogas from corn as an energy crop	1.59	0.7	1.11	1.0	1.11

***Source:** compiled by the authors*

Based on the data in Table 1, Ukraine has sufficient potential for the production of biogas from all types of bio-raw materials, but high initial investments and significant payback periods for projects negate the advantages of this technology. The situation is gradually changing with the increase in tariffs for the main types of energy resources in Ukraine. In proportion to their increase, interest in implementing such projects is also growing. New biogas plants will be built in Ukraine in the near future. Analysing the long-term activity of the Agro-Oven enterprise, it can be concluded that it is possible to reduce the payback period of a biogas project by successfully combining several technologies. The most efficient biogas technologies should combine the use of anaerobic digestion and accelerated biothermal composting technologies sequentially (Fig. 2).

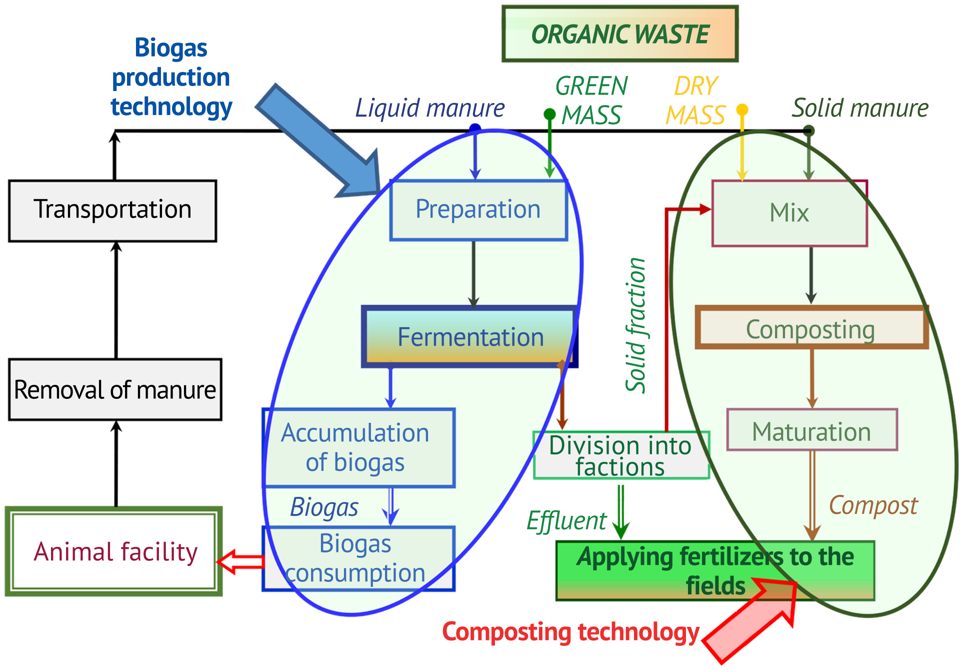

Figure 2*. Anaerobic processing of organic agricultural waste with the production of biogas and fertilisers*
Source: *(Shevchenko & Lyashenko, 2012)*

Based on Figure 2, biogas systems should be designed together with composting and organic fertiliser production systems, considering the physical and chemical properties of manure, in particular, humidity (Fig. 3).

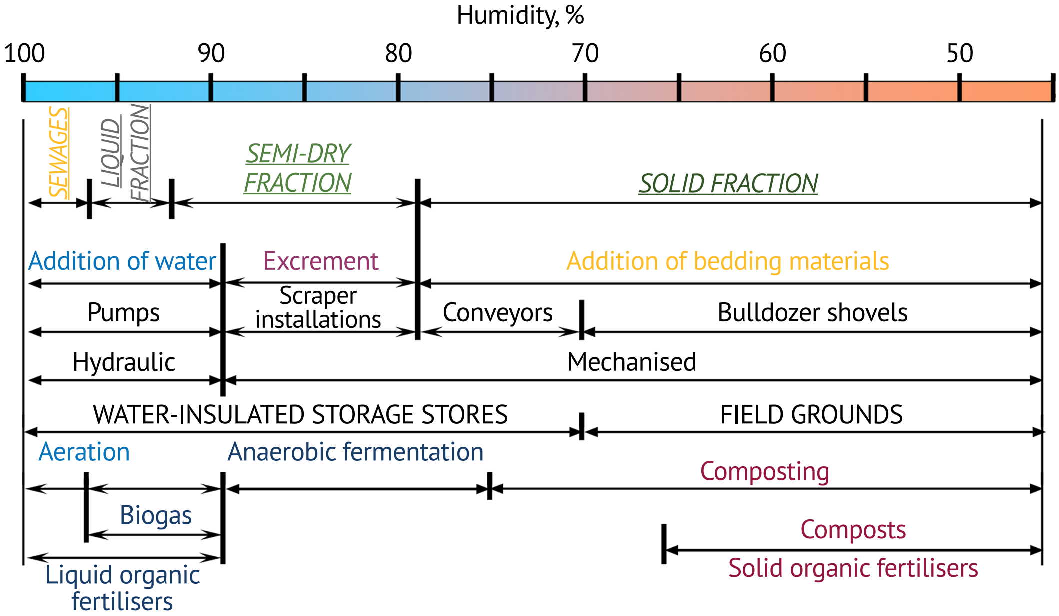

Figure 3*. Scheme of technological aspects of manure processing depending on its humidity*
Source: *compiled by the authors*

Over the past 10 years in Ukraine, the vast majority of cattle manure was litter and came from households (Fig. 4). Admittedly, the energy balance of feed costs in the body of cattle allows determining the energy of "fuel" biogas at the level of 17% and the energy of solid fertiliser – at the level of 35.5%. Setting up organic waste processing equipment for a specific technological process should take place in accordance with the volume of bio-raw materials that can be used for the production of one (biogas) or another (fertiliser) final product. Technologies, in turn, must consider the degree of decomposition of organic matter depending on the final product – biogas or organic fertilisers.

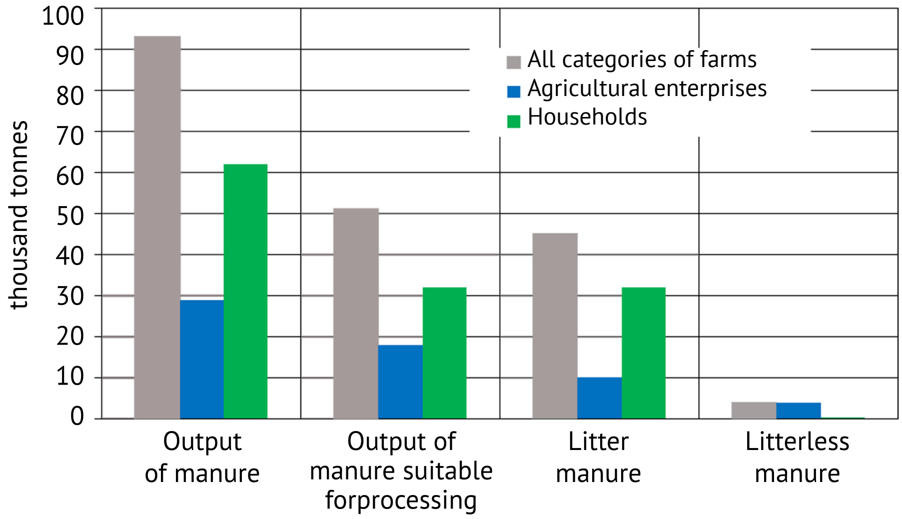

Figure 4. *Annual production of cattle manure in Ukraine during 2010-2020*
Source: *calculated by the authors*

According to the authors' calculations, to meet Ukraine's needs for biogas, it is necessary to build about 3,000 biogas plants with an average volume of 1,000 m^3, including: 295 installations at pig farms; 130 installations at poultry farms; 2,478 installations in other livestock farms and processing enterprises.

However, despite the prospects, the widespread introduction of biogas technologies is hindered by a number of factors, in particular, the most significant are technological ones:

– lack of tested Ukrainian technologies for solid-phase methane fermentation of litter manure, which accounts for more than 80% of the country's manure biomass (Fig. 4);

– lack of modern highly efficient installations for the production and use of biogas;

– lack of multi-tonnage agricultural waste processing plants for the production of biologically active and highly efficient fertilisers to accelerate energy-saving reproduction of soil fertility;

– lack of coordination between research and development activities in this area and specialised design institutions and equipment manufacturers.

Researchers (Deng *et al.*, 2020; Chadwick *et al.*, 2015) note the similarity of technological factors that hinder the introduction of biogas technologies in Singapore and China.

As the experience of functioning of the Agro-Oven enterprise shows, the efficiency and use of the potential of biogas technologies and bioenergy installations largely depends on the main purpose of their creation, because this determines their technical equipment, complexity, completeness, and hence the cost of capital structures and maintenance. In particular, the introduction of such installations provides for:

– rational use of biomass energy of agricultural waste (animal, plant, municipal origin, etc.) with the production of biofuels and attracting additional non-conventional and renewable energy sources in the form of biogas to the energy balance. The real potential for obtaining biogas in the agro-industrial complex of Ukraine only from the processing of livestock waste (manure) is 0.3-0.5 billion m^3/year, while the total biogas potential in animal husbandry is 2.5 billion m^3/year;

– obtaining high-quality biofertilisers (more than 10-20 million tonnes/year) and thus increasing the yield of agricultural crops by 10-20%, and most importantly – meeting the requirements for preserving the humus composition and fertility of significantly depleted soils in Ukraine in recent years;

– diversification of agricultural production through trade in new products (bio-phytopreparations, vitamins), quotas and reduction of greenhouse gas emissions (carbon dioxide and methane), which make up 96% of the biogas composition. The average profit from the sale of greenhouse gas emission quotas can reach more than EUR 4 billion per year in animal husbandry alone;

– environmental protection: reducing or preventing environmental pollution by secondary products (waste) of agricultural production; improving the environmental, sanitary, and hygienic situation in the region (by deodorisation, devitalisation, disinfection, treatment of wastewater from organic substances);

– more complete involvement of chemical elements in the natural cycle, in particular biogenic ones – C, N, P, K, including in the cycle "soil environmen – farm – soil environment", restoration and stabilisation of soils and their fertility. During anaerobic methane fermentation, more than 55% of carbon is not only not lost, as as a result of manure decomposition during composting, but is disposed of in the form of high-calorie methane gas. Accordingly, nitrogen losses are reduced from 20-25% to 1.5-3%. In general, during fermentation, the total content of the main biogenic elements of manure does not change, with the exception of ammonia nitrogen, an increase in the content of which up to 15% increases the digestibility of agrochemical (biogenic elements) substances by plants, especially in the first year of application;

– reduction of the cycle, energy and capital costs in the treatment systems of "secondary" waste media and wastewater in comparison with standard solutions.

As part of the study, the distribution of the potential of animal husbandry bio-waste across historically formed natural and economic zones and administrative territories of Ukraine is analysed. According to the results of the analysis, the first place – more than 43% belongs to the forest-steppe zone, followed by the steppe zone located in the southern part of the country, which accounts for 30% of possible biogas production. In the north-western zone of Polissia, the potential of biogas is 27%. Thus, rural residents of the steppe zone should be considered the most potentially provided with biogas, and residents of Polissia should be considered the least provided. Notably, in the steppe zone, there is a significant scientific and industrial potential for Ukraine, sufficient for the production and equipping all regions with modern equipment for processing manure to obtain environmentally friendly biofertilisers and biogas. Areas with significant opportunities for biogas production due to developed animal husbandry (more than 100 million m^3/ year) include Vinnytsia, Khmelnytskyi, Lviv, Poltava, Zhytomyr, Chernihiv oblasts, etc.

It is possible to increase the efficiency of bio-waste processing and increase the profits of enterprises by developing a manure processing system with simultaneous production of biogas and compost. For this purpose, the technology of accelerated biothermal composting is analysed (Fig. 5).

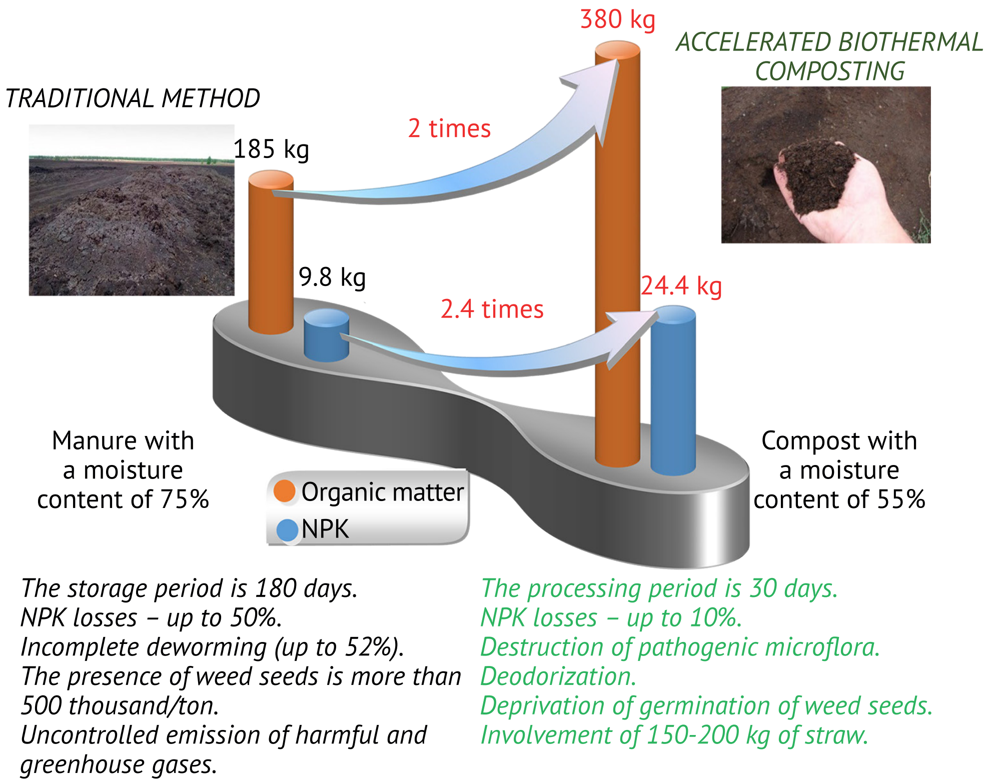

***Figure 5**. Efficiency of accelerated biothermal composting in the calculation of processing 1 tonne of cattle manure*
***Source:** compiled by the authors*

This type of composting can be not only an application to biogas technologies, but also an independent technological solution to the problem. Accelerated biothermal composting – is a controlled process that allows setting and maintaining optimal conditions necessary for the flow of microbiological processes (humidity, temperature, structure, physicochemical composition, the presence of biogenic substances) and minimises the time of waste processing into high-quality compost. This type of composting can be used: directly at livestock facilities of various sizes with litter and non-litter keeping of animals; during the reconstruction of existing sites for compost production, including as part of biological manure processing facilities; in all climatic zones of Ukraine. For example, 1 tonne of cattle manure processed using accelerated biothermal composting allows increasing the production of organic matter by 2 times and NPK by 2.4 times (Shevchenko *et al.*, 2011). For comparison, according to studies (Bohacz, 2018) using the same technology, the production of organic matter from 1 tonne of cattle manure increases by 1.78 times, and NPK – by 2.19 times. Accelerated biothermal composting technology requires preliminary preparation of mixtures for composting and creation of optimal conditions for the passage of microbiological processes in the prepared mixtures. This technology provides for the completion of the process with the minimisation of necessary technological and resource costs; quality assurance of the final product – compost as an organic fertiliser; sanitary and environmental safety of both the production itself and the resulting compost.

For a comparative analysis of the use of two technologies for the disposal of cattle manure, the algorithm and calculation method developed as part of the study were used (Table 2). For anaerobic digestion, 450 kg of water was added per 1,000 kg of cattle manure, and for accelerated biothermal composting – 220 kg of straw.

***Table 2**. Comparative indicators of anaerobic digestion technology and accelerated biothermal composting technology during cattle manure recycling*

Name	Designation	Unit of measurement	Anaerobic digestion technology	Accelerated biothermal composting technology
Volume of processing of cattle manure	M_g	kg	1,000	
Chemical properties of manure (by dry matter)				
Nitrogen		%	3.2	
Phosphorus		%	1.8	
Potassium		%	5	
Introduced components:				
Water	M_w	kg	450	–
Straw	M_{str}	kg	–	220
Volume of prepared mass	M_{prp}	kg	1,450	1,220
Humidity	W	%	92	75
Organic matter content:	R_{orm}	kg	98.60	291.78
Energy potential depending on the degree of decomposition of organic matter, E:				
10%		MJ	–	525.20
15%		MJ	–	787.80
20%		MJ	390.46	1,050.39
25%		MJ	–	1,312.99
30%		MJ	585.68	1,575.59
40%		MJ	780.91	
50%		MJ	1,015.19	
Equivalent consumption of energy produced for own technological needs				All the released thermal energy is used to evaporate moisture
15%		MJ	–	787.80
20%		MJ	230.03	1,050.39
25%		MJ	–	1,312.99
30%		MJ	287.54	1,575.59
40%		MJ	345.04	
50%		MJ	–	
10%		kg	–	-175.07
15%		kg	–	-262.60
20%		kg	1,109.35	-350.13
25%		kg	–	-437.66
30%		kg	1,132.35	-525.20
40%		kg	1,155.36	

Table 2, Continued

Name	Designation	Unit of measurement	Anaerobic digestion technology	Accelerated biothermal composting technology
50%		kg	1,182.97	
Solid fraction (compost) transportation volumes			Solid fraction after separation of the fermented mass	Compost
10%		kg	–	1,015.48
15%		kg	–	913.36
20%		kg	320.93	811.23
25%		kg	–	709.11
30%		kg	288.07	606.99
40%		kg	255.20	
50%		kg	215.76	
Transportation costs (conditional, for the degree of decay of 30%):			Fermentation	Composting
manure to sewage treatment plants (0.5 km)		t*km	0.50	0.50
water (0.5 km), straw (5 km)		t*km	0.23	1.10
liquid fraction (5 km)		t*km	5.66	0.00
solid fraction/compost (5 km)		t*km	1.44	3.03
Total		t*km	7.83	4.63
Vehicles				
Liquid fertilisers			Tractor + tanker	–
Solid fertilisers			Tractor + spreader	Tractor + spreader
Properties of solid fertilisers				
Dry matter content		kg	34.57	217.43
Organic matter content		kg	23.78	149.59
Macronutrient content:				
N		kg	1.11	6.96
P		kg	0.62	3.91
K		kg	1.57	10.87

Source: *compiled by the authors*

It is evident that the results of calculations for the disposal of pig manure or bird droppings will be different, but the algorithm and methodology of these calculations will remain unchanged. Figure 6 shows the calculation of transport vehicles costs for typical implementation conditions for each of the technologies.

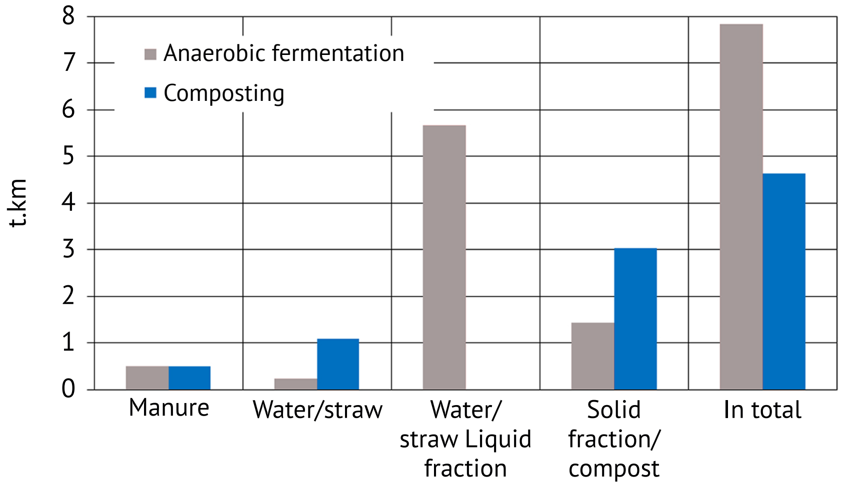

Figure 6*. Structure of transport costs in the implementation of comparative technologies for organic waste disposal (t.km)*
Source: *calculated by the authors*

The results of calculations are the basis for analysing the economic feasibility of using various technological solutions for organic waste disposal. The structure of calculations, depending on the realities of the agricultural activity of a given enterprise, allows determining which area of organic matter processing should be preferred and at what stage of development. Calculations show that as a result of processing 1 tonne of cattle manure, 23.22 g^3 of biogas can be obtained (with an energy equivalent of 510 MJ), and by applying the obtained organic fertilisers to reduce energy costs for the production of an equivalent (according to NPK) quantity of mineral fertilisers by 895 MJ. However, the cost of building and maintaining a biogas system is such that at the first stage of cattle manure recycling, it is more expedient to apply accelerated biothermal composting technology.

Zhou *et al.* (2012) note that it is advisable to process cattle manure in the form of mixtures with the addition of plant residues of agricultural production, and the operation of preliminary microbial treatment of these residues should be included in the anaerobic digestion technology. For example, the addition of pre-treated corn plant residues to cattle manure increased the yield of biogas during anaerobic digestion by 23.2%-40.7%. In turn, the researchers (Kudria *et al.*, 2020) also note the need for preliminary preparation of mixtures for composting and the creation of optimal conditions for the passage of microbiological processes in the prepared mixtures in the process of accelerated biothermal composting during the recycling of cattle manure. This should be considered when performing further calculations for the effective disposal of cattle manure and bird droppings.

Researchers (Ji *et al.*, 2022) note that the development of pig farming can also be a powerful source of bio-waste for the production of biogas and compost. In particular, in the structure of the energy potential of biowaste of the people's Republic of China, pig farming occupies more than 50% in terms of the volume of manure yield. Thus, potentially the share of biogas from pig waste can be 17% or more. In addition, pig manure effluents are the largest environmental pollutants and their processing into compost or biogas will contribute to compliance with mandatory environmental protection measures.

The cost of biogas, in turn, will be economically substantiated when the ratio of the cost of biogas production and the unit cost of other energy carriers is adequate to the ratio of the corresponding energy values in units taken during their implementation. According to researchers from the EU countries (Bai *et al.*, 2020; Deng *et al.*, 2020), energy costs for the implementation of the technological process of biogas production in countries with warm climates are minimal, and the share of commercial biogas is quite high – from 80 to 100%, while in temperate and cold climates (for example, in Germany, Ukraine) this share is in the range from 30 to 50%. For farms in Denmark, the Netherlands, and Germany, the return on investment in biogas technologies for cattle from 180 to 200 cows is 5-7 years old.

Thus, biotransformation of biomass energy into biogas by methane fermentation allows comprehensively solving a number of important tasks – energy, social, agrochemical, and environmental (Channarayappa *et al.*, 2018; Yoshizaki *et al.*, 2013). An important component of the efficiency of biogas technology is the existence, along with direct effects (obtaining biogas and high-quality fertilisers), of a number of indirect effects, the significance of which is based on both economic indicators and national priorities. The latter include: reducing the energy consumption component in the cost of production; saving energy resources in the rather expensive production of mineral fertilisers; reserving energy for the purpose of continuous implementation of the main technological processes in the production of livestock products; reducing the load on the soil from the use of herbicides.

CONCLUSIONS

The introduction of biogas technologies is economically feasible in full only within the framework of the functioning of closed systems for the production of crop and livestock products. Organic waste of animal origin is the main source of soil fertility renewal. Organic fertilisers with biogas should become a highly marketable product.

The main source of biogas production is cattle manure, which accounts for more than 84%. At the same time, the share of the potential energy of biogas reaches 85% (from the number of cattle – 63%). The use of biowaste from the livestock industry for the production of biogas should be limited to the level of 25 to 30% of organic decomposition. The full use of organic waste from this industry for energy purposes is impractical.

The efficiency of the manure processing system with simultaneous production of biogas and compost is, depending on the economic condition of the enterprise, 10 to 35% higher compared to the production of only biogas or only compost. As a result of processing 1 tonne of cattle manure, 23.22 g^3 of biogas can be obtained (with an energy equivalent of 510 MJ), and by applying the organic fertiliser produced, the energy inputs for producing an equivalent (at NPK) amount of mineral fertiliser can be reduced by 895 MJ. Due to the high costs of building and maintaining a biogas system, it is advisable to use accelerated biothermal composting at the first stage of waste disposal.

Further study will be aimed at developing the basic principles of organic farming based on an economically and environmentally sound level of bioconversion of organic biomass in artificial conditions to provide nutrition to the soil environment and field crops.

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Енергоекологічні передумови вибору технологій переробки органічних відходів тваринництва

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Анотація. Для сучасної України та країн Європи актуальними є питання відновлення ґрунтів після інтенсивного обробітку та зниження собівартості аграрної продукції шляхом включення в енергозабезпечення технологічних процесів енергії на основі альтернативних джерел. Тому значна увага приділяється розвитку біогазових технологій та виробництву органічних відходів. Метою дослідження є підвищення ефективності системи переробки гною з подальшим виробництвом біогазу і компосту шляхом послідовного виконання технологій анаеробного та аеробного зброджування. Представлено економічно доцільні шляхи використання органічних відходів тваринництва. Доведено, що впровадження біогазових технологій є економічно доцільним лише за умов функціонування замкнених систем виробництва продукції рослинництва і тваринництва. Найбільш ефективним виявилося поєднання послідовної реалізації технології анаеробного зброджування та прискореного біотермічного компостування. Анаеробне метанове зброджування, на противагу процесу компостування біосировини, дозволяє понад 55 % вуглецю утилізувати у вигляді висококалорійного газу метану, за рахунок чого втрати азоту знижуються із 20–25 % до 1,5–3 %. Аналітичні дослідження дозволяють стверджувати, що в результаті перероблення 1 тони гною великої рогатої худоби можна отримати 23,22 м^3 біогазу з енергетичним еквівалентом 510 МДж. Також показано, що за рахунок внесення вироблених шляхом прискореного біотермічного компостування органічних добрив енерговитрати на виробництво еквівалентної (за NPK) кількості мінеральних добрив скорочуються на 895 МДж. Проте, слід враховувати, що за умов побудови та обслуговування біогазової системи висока вартість стартових і поточних витрат зумовлює на першому етапі перероблення біосировини використовувати технологію прискореного біотермічного компостування. Отримані результати можуть бути покладені в основу осучасненої методології розрахунків доцільності застосування тієї чи іншої технології залежно від умов функціонування аграрного підприємства та технологічного завдання щодо обсягів виробництва готової продукції. Це дозволить визначати раціональні параметри біоенергетичної системи та підвищити енергоекологічну ефективність процесів виробництва біогазу та високоякісних компостів з органічної сировини

Ключові слова: анаеробне метанове зброджування, прискорене біотермічне компостування, біоенергоконверсія, органічна сировина