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An advanced European overview of the bioenergy efficiency of using digestate from biogas plants when growing agricultural crops

Abstract: The paper highlights calculations of bioenergy indicators when growing corn for grain and vegetable crops in Ukraine. The research results indicate the economic benefit of growing these crops for all the variants studied. Our research established that an increase in the bioenergy efficiency of the production of these crops is achieved due to the use of different rates of fertilizer application. The increase in productivity that was obtained as a result of the implementation of farming practices exceeds additional costs associated with the use of fertilizers. This confirms the economic benefit of producing these types of crops due to the enhanced bioenergy efficiency achieved through the optimal application of fertilizer.

The conducted research confirms the high energy efficiency of the bio-organic fertilizer (digestate) and the energy-saving technology of growing crops which were studied. High values of the coeffi-

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cients of energy efficiency were also observed in the variants with the simultaneous application of mineral fertilizers ($N_{90}P_{90}K_{90}$) and digestate-based bio-organic fertilizer "Efluent" (55.0 t/ha) on experimental sites of corn grown for grain (3.05–3.07), carrot (1.41–1.45) and red beet (1.97–2.00), but the cost of these variants also appeared to be the highest. Scientific research has used new methods and technologies for the effective processing of livestock waste in order to obtain organic fertilizer, which can be used to improve soil fertility and increase crop yields on the one hand, and biogas production as an energy-efficient process that has significant potential for producing ecologically clean and renewable energy on the other. The proposed approach to achieving energy efficiency helps to increase crop yield without increasing fertilization costs.

Keywords: digestate, efluent, energy security, bioenergy efficiency, energy efficiency ratio

Introduction

Increasing energy independence is one of the priorities for the development of any country in the world, including Ukraine. To achieve this goal, it is appropriate to implement a policy of using renewable energy sources, especially in the development of bioenergy. Ukraine possesses a large area for agricultural production, which can both meet food needs and produce large amounts of raw materials that can be used for the production of biofuels. The use of biomass as an energy source is of great importance in the developed countries and throughout the world as a whole. Since oil and gas prices are rising and energy demand is growing, the use of biomass is becoming increasingly attractive from the economic point of view. However, it is important to consider not only economic aspects but also biological and ecological issues. The use of biomass simultaneously solves two important problems: meeting energy needs and protecting the environment. Using biomass as an energy source is a renewable process because biomass can be grown, recovered and reused. In addition, burning biomass in the process of energy production is less harmful to the environment due to the fact that carbon emissions are offset by the natural process of photosynthesis. Modern technologies for continuous energy production from biomass (e.g. biogas plants, pellet plants and biomass gasification processes) are quite efficient and are becoming much more common in the world. These technologies enable the use of biomass for the production of heat, electricity and other types of energy while ensuring a sustainable energy supply and reducing the negative impact on the environment.

The main criteria for determining the expediency of the introduction of agricultural products or agricultural technology in general are their economic and bioenergetic efficiency. In today's difficult economic conditions, justification of rational agricultural management must be considered as one of the most important conditions for increasing production. The issue of the efficiency of production of corn for grain and vegetable crops in Ukraine is gaining special relevance.

1. Literature review

Global reserves of exhaustible fossil carbon fuels are rapidly decreasing, which forces the global community to intensively implement renewable energy sources, among which plant biomass holds the leading position. It covers about 40–50% of energy consumption in the structure of renewable energy sources in the developed countries. In addition, a gradual replacement of coal, natural gas and oil refining products with biofuel from plant biomass, which is under constant reproduction in volumes that exceed consumption, ensures the restoration and preservation of the carbon dioxide balance in the atmosphere (Dubrovin et al. 2004).

Agriculture is the second largest source of greenhouse gas emissions in the world after burning fossil fuels for energy production; however, thanks to new high-precision cultivation technologies and innovative products, the sector is expected to contribute to the reduction of global warming (Canadell and Schulze 2014; Kaletnik et al. 2020).

According to the experts, a significant growth of the global bioenergy potential of agricultural lands is predicted by 2050. Estimates from 64 to 161 EJ per year−1 indicate a wide range of possible uses of bioenergy from agricultural sources (Haberl et al. 2011). However, it is important to consider that the development of the global demand for food and animal feed also has a great impact on the availability of biomass for energy production. Increasing food demand may limit the amount of biomass available for energy use. Therefore, a detailed analysis of agriculture is an important step for the effective use of biomass as an energy source. It enables us to take into account the competition between the use of biomass for food, animal feed and energy. This analysis can also reveal optimal ways of using agricultural resources for biomass production, ensuring sustainable development and the preservation of the environment.

The biological fertility of soils is determined by a large number and variety of soil microflora that functions and provides the soil ecosystem (Arthurson 2009). Useful soil microflora creates favorable conditions for the growth and development of plants and increases soil fertility, and in particular, limits the mineralization of organic matter (Karimi et al. 2020; Baumann et al. 2012) and creates a barrier effect for pathogen populations (Vivant et al. 2013), supports the soil structure (Le Guillou et al. 2012), increases drought resistance of plants (Prudent et. al. 2020), reduces atmospheric pollution (Abis et. al. 2020), and on a more global scale, supports the stability of soil functioning (Maron et. al. 2018).

The intensive use of high doses of mineral fertilizers, especially nitrogen (N), has led to significant problems including high cost, nitrate pollution and loss of soil carbon (C). Considering a growing need for environmentally friendly agricultural production, organic fertilizers have become an object of extensive research. Composts, manures and other organic materials are used to improve soil fertility, since they contain natural nutrients and help to support biological life in the soil (Koszel and Lorencowicz 2015; Reuland et al. 2021; Kovačević et al. 2022; Lohosha et al. 2023a).

Digestate, which is a product of biogas plants and obtained from biomass, is also being investigated as an organic fertilizer intended to improve soil fertility. Digestate contains nutrients, e.g. nitrogen, phosphorus and potassium, as well as organic material that helps retain moisture and support microorganisms in the soil. The use of digestate as an organic fertilizer can be an effective way to replace mineral fertilizers, reduce the negative impact on the environment and ensure sustainable development of agriculture.

Digestate can quickly become a good source of readily available macro elements (carbon (C), nitrogen (N), phosphorus (P), potassium (K), sulfur (S), calcium (Ca), magnesium (Mg) and trace elements for plants and soil and can partially replace the application of animal manure or mineral fertilizers (Hammerschmiedt et al. 2022; Brtnicky et al. 2022; Karimi et al. 2022). It also contains a part of organic matter, which has a positive effect on the physical and chemical properties of soils (Odlare et al. 2008). Digestate can effectively compete with mineral fertilizers in increasing the productivity of agricultural crops and soil fertility (Verdi et al. 2019).

For Ukraine, bioenergy is one of the strategic areas for developing the sector of renewable energy sources, considering the country's high dependence on imported energy sources, primarily natural gas, as well as the great potential of biomass available for energy production (Lohosha et al. 2023b).

Many countries have traditionally used forest biomass to get energy, and a number of research projects are being currently undertaken to assess the impact of forest bioenergy on sustainability parameters (Mola-Yudego et al. 2017).

Due to the growing threat of global warming and limited fossil energy sources, bioenergy and biogas production have become an important goal aimed at reducing the effects of climate change, achieving energy security, providing resources and ensuring the sustainable development of agriculture (Shakoor et al. 2020; Thangarajan et al. 2013; Pryshliak et al. 2022).

Over the last decade, the global production of biogas has tripled, which makes it possible to partially replace fossil fuels, and the production of biogas through anaerobic fermentation, which generates a significant amount of by-products (digestates) (Karimi et al. 2022; Palamarchuk et al. 2020; Urra et al. 2019). In many countries, the potential of biogas production, although it has high efficiency, has not yet been fully utilised (Meyer et al. 2018; Gontaruk et al. 2024).

Biogas production and digestate application may have a significant impact on the reduction of greenhouse gas emissions and the enhancement of soil carbon sequestration. The main regions of biogas production include the following: 1) Europe, which is the world's largest biogas producer, producing more than 18 million tons of oil equivalent of biogas in 2018 and European countries actively use biogas production technologies, in particular, anaerobic transformation of organic materials, including waste from the food industry and agriculture, into biogas; 2) China, which is one of the largest producers of biogas in the world, producing approximately 7 million tonnes of oil equivalent of biogas and China's urbanization contributes to significant production of organic waste that can be used for biogas production; 3) the USA also has significant potential for biogas production, with production of about 4 million tons of oil equivalent of biogas and in the USA, biogas is produced from a variety of sources, including organic waste, farms, and municipal waste (IEA 2018). These regions use biogas as an alternative energy source, which helps to reduce the use of traditional hydrocarbon fuels and reduce greenhouse gas emissions. Germany holds a leading position in the European biogas market, with two thirds of European biogas plants. Some countries including the UK, France, Switzerland, Denmark and the Netherlands have also accelerated the development of the biogas industry over the past ten years. They show significant interest and the ability to use biogas as a renewable energy source (International Energy Agency (IEA) 2019) (IEA 2019).

The policy of subsiding through EU funds is contributing to the rapid development of biogas plants in Europe. In the Czech Republic, a rather extensive introduction of biogas plants has been recorded in the last three years. Along with the increase in the number of biogas plants, which currently amount to about 550, an increase in the production of digestate as a by-product of biogas production can be observed. Liquid digestates (fugates) contain more mineral nitrogen (typically 5–6% of dry weight) and less organic carbon than the unfermented input material (Johansen et al. 2013a) and C:N in the digestate can be ten times lower than in farmyard manure (Möller and Müller 2012).

Biogas production using anaerobic biomass fermentation technologies can have a positive impact on the environment for several reasons (Johansen et al. 2013b):

1. Decrease of greenhouse gas emissions: the anaerobic fermentation of biomass in biogas plants makes it possible to obtain biogas, which mainly consists of methane and carbon dioxide. Using biogas instead of fossil fuels such as oil and coal to produce electricity and heat helps to reduce emissions of greenhouse gases such as carbon dioxide into the atmosphere.

2. Reduction of the use of chemical fertilizers: the digestate remaining after the anaerobic fermentation of biomass can be used as an organic fertilizer for fields. The use of digestate helps to increase soil fertility and can help to reduce the use of chemical fertilizers, especially nitrogen fertilizers, which can have a negative impact on the environment if they are used excessively.

3. Reduction of the risk of weed seed and pathogen spread: the process of anaerobic fermentation in biogas plants is high-temperature and requires specific conditions that contribute to the destruction of weed seeds and pathogenic microorganisms. Thus, the digestate obtained after fermentation has a lower risk of spreading these undesirable organisms in the field.

Initially, the research on digestates was aimed at evaluating the effective reduction of odor, decomposition, and pathogens (Nkoa 2014). Following on from this, a significant amount of research was intended to study the use of digestates based on manure or sewage sludge as fertilizers (Ni et al. 2017; Borowski et al. 2018).

The interest of farmers in using digestate is related to the lack of a sufficient amount of organic fertilizers, the high cost of mineral fertilizers, an imbalance of organic matter and a large amount of organic waste in the soil (Lohosha et al. 2022).

The use of mineral nitrogen fertilizers causes an increase in greenhouse gas emissions (on the 35^{th} day after application) compared to the use of organic fertilizers, in particular digestate (Doyeni et al. 2022). Biogas production waste, i.e. digestate, can replace mineral fertilizers in the biomass-biogas-biomass cycle (Walsh et al. 2012; Nabel et al. 2017).

There is a wide range of microorganisms that participate in the anaerobic process of biogas and digestate formation. Biogas is a combustible gas containing methane (60–70%), carbon dioxide and a small amount of other gases and components (Simeonov et al. 2012; Zaharinov 2013).

For anaerobic fermentation (AD) in bioreactors and the production of biogas, substances having an organic structure can be used, in particular, purified wastewater, plant residues, grass silage, energy crops, agro-food industry waste (part of solid household waste, including fruit and vegetable residues, canteen waste, kitchen waste), green waste (grass clippings, leaves), livestock waste (pig and cow dung, chicken droppings) and food waste (animal fats, used cooking oil, restaurant degreasing tanks) (Bhatt and Tao 2020; Kathijotes et al. 2015; Tilvikiene et al. 2020), wood industry waste (Rawoof et al. 2021; Honcharuk et al. 2023), fishing and aquaculture waste (European Parliament 2009).

Sustainable use of digestate in agricultural systems has both positive and negative environmental impacts (Möller and Müller 2012; Nkoa 2014; Lohosha et al. 2018; Palamarchuk and Krychkovskyi 2020a). One of the benefits of using digestate is a high content of nutrients compared to raw materials, mainly nitrogen in the form of NH^{4+} (Gutser et al. 2005; Masse et al. 2011). However, during anaerobic digestion, a significant amount of nitrogen (N) is released in the form of ammonium and carbon (C) in the form of methane and carbon dioxide. However, a significant portion of nutrients such as nitrogen (N), phosphorus (P) (Slepetiene et al. 2020) and potassium (K) (Barłóg et al. 2020) are retained (Béghin Tanneau et al. 2019).

Chemical reactions during the biogas process can reduce the mobility of Mg, Ca, P, and S through the formation of calcium and magnesium phosphates, such as carbonates, hydroxyapatites, and iron sulfides (Bubaker et al. 2012; Zirkler et al. 2014).

Nitrogen contained in digestate is mobile and easily available to plants, but it can also be easily lost due to slow microbiological activity associated with low temperatures, which can reduce the efficiency of digestate fertilization, as has been observed in cauliflower crops (Alburquerque et al. 2012).

The application of digestate into the soil helps to reduce the carbon and nitrogen content, while at the same time, the phosphorus and potassium content increases (Doyeni et al. 2021). Agrochemical composition and the characteristics of digestate depend, to a greater extent, on the properties of the substrate and the method of animal feeding (Häfner et al. 2021).

Manojlovic et al. (2021) established that before using digestate in agriculture, it is important to study its composition and to take into account availability of heavy metals. A high concentration of heavy metals in fertilizers and soil conditioners can have a negative impact on soil fertility and environmental safety.

There are regulations and maximum permissible concentrations of heavy metals in fertilizers, soil conditioners and special agents used in agriculture. For example, in many countries there are normative acts regulating the content of heavy metals in fertilizers and their application in the field. When using digestate as an organic fertilizer, it is important to monitor the levels of heavy metals in the soil and regulate their input. This can be achieved by setting the limits of permissible concentrations of heavy metals in fertilizers, controlling their use and taking into account the potential negative impact on soil and plant fertility. In addition, it is recommended to conduct regular soil analyses to determine the levels of heavy metals and to respond in time to any deviations from the accepted standards. Such monitoring will help to ensure environmental safety and the preservation of soil quality while applying digestate and other organic fertilizers.

The quality and structure of organic matter in biogas digestates depends on the raw materials for biogas production and the technology applied, and this can affect availability of heavy metals

(Törnwall et al. 2017; Kupper et al. 2014). For example, pig manure contains more potassium (Zhan et al. 2020; Guilayn et al. 2019), while co-fermented cattle manure increases phosphorus content (Bachmann et al. 2011). Thus, digestate (as an organo-mineral fertilizer) can provide the same amount of nutrients as mineral (Riva et al. 2016) or organic fertilizers like manure (Alburquerque et al. 2012).

The application of digestate into the soil improves nutrient cycling, carbon fixation and structure, reduces the need for mineral fertilizers (Przygocka-Cyna and Grzebisz 2018; Holm-Nielsen et al. 2009), slows down the mineralization of humus and has a positive effect on beneficial soil microflora (Dragicevic et al. 2018), increases its nitrogen (N) content, especially digestate rich in ammonium nitrogen (NH4-N), a form of nitrogen that is readily absorbed by plants (Jamison et al. 2021). The ratio of mineral nitrogen to the total nitrogen content is an important indicator of its influence on the cycle and transformation of nitrogen in the soil during plant growth and development.

It is also worth noting that the improper use, fermentation and sedimentation of raw materials for biogas plants can lead to environmental pollution (Zaharinov 2013; Kaletnik et al. 2021). The use of digestate compared to manure ensures an increase in hay yield (Bougnom et al. 2012). Digestate can be used as a substrate for growing microalgae (Bauer et al. 2021; Li et al. 2022). The application of digestate obtained on the basis of the anaerobic fermentation of pig manure does not affect the quality of wheat grain and straw compared to mineral fertilizers (Doyeni et al. 2021; Šimon et al. 2015).

Today, research into the possibility of replacing peat with digestate or creating peat mixtures is widely conducted (Ceglie et al. 2015). Peat is one of the most important substrates in gardening and vegetable growing (Stoknes et al. 2018). The substitution of 50% peat in compost (AD/peat) provided the same yield of basil (*Ocimum basilicum*) as using peat alone. No symptoms of toxicity or deficiency were found in the 50% mixture; however, the moisture-holding capacity slightly decreased when part of peat was replaced (Asp et al. 2022).

2. Materials and methods

Specialized, accredited and certified laboratories of Prime Lab Tech and the Institute of Applied Biotechnology were used to analyze microbiological and agrochemical composition. In the Prime Lab Tech laboratory internationally certified according to ISO 22000, which is a standard for food safety management systems, the agrochemical composition of pig manure was determined as the main component for obtaining digestate. Results of the analysis were performed in accordance with the current State Standards of Ukraine (DSTU) and methodical recommendations. A detailed analysis of microbiological composition of organic fertilizer (digestate) and pig manure was conducted in the biolaboratory of the Institute of Applied Biotechnology.

Bioenergy efficiency was calculated using the data of technological maps of crop cultivation and taking into account all cost items including the cost of fuel and lubricants, fertilizers, yield, seeds, pesticides and other means of production according to the prices of 2021.

Bioorganic fertilizer "Efluent" was obtained due to the anaerobic fermentation of pig manure in special biogas stations for fourteen days. During this period, organic substances of the manure are decomposed under the influence of anaerobic microorganisms, which leads to the release of biogas and the production of bioorganic fertilizer. The obtained bioorganic fertilizer "Efluent" has a certificate of conformity (TU U 20.1-38731462-001:2018) and it has been patented in Ukraine (Palamarchuk and Krychkovskyi 2019). This proves that it meets the requirements of quality and safety standards, and is legally protected on the territory of Ukraine.

Energy efficiency of the fertilizer use was calculated according to generally accepted methodology (Kovalchuk 2002). Research data was processed using dispersion, correlation and regression analysis using the method developed by Zhuchenko (1980). A personal computer with the installed specific application software for Windows, namely Excel and Statistica, was used to process data.

Agrochemical analysis of bioorganic fertilizer "Efluent" is shown in Table 1.

TABLE 1. Results of agrochemical analysis of bioorganic fertilizer "Efluent" (2019–2020)

TABELA 1. Wyniki analizy agrochemicznej nawozu bioorganicznego „Ścieki" (2019–2020)

No.	Name of indicators [units of measurement]	Trial results
1.	Saline pH	8.2–8.5
2.	Mass fraction of moisture [%]	97.5–98.4
3.	Dry matter [%]	1.6–2.5
4.	Ash content in nature/in completely dry matter [%]	0.60/34.5–37.3
5.	Content of organic matter in nature/in completely dry matter [%]	1.00/62.7
Macroelements		
6.	Nitrate nitrogen [mg/kg]	18.2 (0.06%)
7.	Ammonium nitrogen [kg/t]	2.3–3.0
8.	Total nitrogen [kg/t]	2.9–4.1
9.	Phosphorus in terms of P_2O_5 [kg/t]	0.9–1.3
10.	Potassium in terms of K_2O [kg/t]	1.8–3.2
11.	Sulfur in terms of SO_3 [kg/t]	0.54
12.	Magnesium in terms of MgO [kg/t]	0.42–0.52
13.	Calcium in terms of CaO [kg/t]	1.1–3.5
Microelements		
15.	Copper [mg/kg]	4.6–19.0
16.	Zinc [mg/kg]	32.0–43.0
17.	Manganese [mg/kg]	14.9–20.0
18.	Iron [mg/kg]	45.1–120.0
19.	Molybdenum [mg/kg]	0.23

According to the conducted agrochemical analysis of organic fertilizer "Efluent", no heavy metals in toxic quantities were detected.

The scheme of the experiment included three crops (corn grown for grain, carrot and red beet) and different rates of the application of "Efluent" digestate (25, 35, 45 and 55 t/ha).

3. Results and discussion

The possibility of making a profit from digestate when using it as a fertilizer is currently the most ambiguous, since the market prerequisites for this have not yet been formed. An example of estimating the market value of digestate from the main types of raw materials used for biogas production is shown in Table 2 – this is based on the comparison of the equivalent price of NPK nutrients in mineral fertilizers.

TABLE 2. Price equivalent of NPK content in digestate from some types of raw materials

TABELA 2. Równoważnik cenowy zawartości NPK w pofermencie z niektórych rodzajów surowców

Type of raw material	Dry matter content (DM)	Nitrogen content, N	Phosphorus content, P	Potassium content, K	Digestate output	Price equivalent of NPK in digestates
	% to f.m.	kg/t f.m.	kg/t f.m.	kg/t f.m	t/t f.m.	euro/t
Corn silage	30	4.50	0.75	3.39	0.78	6.42
Sugar beet pulp	13	3.12	0.18	0.52	0.91	1.90
Cattle manure	18	5.76	1.44	7.47	0.92	10.08
Pig manure	2.5	2.30	0.50	0.52	0.99	1.95
Chicken droppings	30	15.00	6.60	5.40	0.89	21.39
Molasses	77.4	11.61	2.32	14.47	0.55	31.71

Notes: f.m. – fresh mass. Estimated at the equivalent price for N, P, K of 0.75, 1.53, 0.68 EUR/kg, respectively. The availability of nitrogen for plant nutrition in the first year of application at the level of 60% is taken into account.

Source: formed on the basis of the authors' research.

Depending on the type of raw material, the content of dry matter and nutrients in it, the digestate formed can have a justified market value of approximately 1.9 EUR/t for digestate from pulp and up to 21.4 EUR/t for digestate from bird droppings, which can be taken into account to calculate the savings when purchasing mineral fertilizers or when selling digestate as an organic fertilizer to a third party.

The given estimate only shows the value of the digestate attributed to a single type of raw material. However, biogas plants usually use a mixture of different types of raw materials, and the volumes of digestate and its fractions after separation are also affected by technological features, such as the degree of recirculation of digestate during the process and the amount of fresh water used for dilution.

In Ukraine, there is no centralized collection of manure at small enterprises, so calculation of the economic energy potential of livestock waste should be performed only for agricultural enterprises with at least 2,000 cattle, 9,000 pigs, and more than 400,000 poultry. Only such enterprises ensure the operation of a cogeneration plant with a capacity of at least 200 kW.

Large pig farms (with over 8,000 pigs) generate a lot of waste that is quite difficult to dispose of, which in turn creates risks for the surrounding natural environment, if not processed (Palamarchuk and Krychkovskyi 2020b). Waste processing in a biogas plant is an effective method of reducing the volume of waste and producing energy, which is a source of environmentally friendly and renewable energy. At the same time, digestate is formed, which contains many useful substances that can be used to fertilize agricultural crops and increase soil fertility. Thus, it is an effective and sustainable method of reducing waste and increasing soil fertility in agriculture.

The main barriers to the use of digestate as an organic fertilizer in Ukraine are as follows:

1) In Ukraine, the majority of biogas plants do not perform regular quality control of the input raw materials and the digestate that is formed by a set of indicators; additionally, technological regimes change during the year, and therefore the physical and chemical composition of the digestate is uncontrolled and unpredictable.

2) Digestate from most biogas plants in Ukraine cannot be considered an organic fertilizer for organic crop production, which is characterized by a lack of demand in the organic production market segment.

3) There is a lack of state control over digestate quality and its handling.

4) There is a lack of its own system of ensuring/standardizing the quality of the digestate produced by the operators of most biogas plants in Ukraine.

For the calculations, the authors used organic fertilizer that is based on pig manure from the pig complex "Subekon" LLC (Vinnytsia region, Tyvriv district, Sutyska village), where more than 12,000 pigs are fattened during the year, as well as organic fertilizer that is based on organic residues of corn, carrot, and red beet.

Based on the research results (Lohosha et al. 2022), it was established that the application of digestate together with mineral fertilizers can lead to a significant increase in the economic efficiency of the production of certain agricultural crops. This can be achieved due to the yield increase compared to additional costs associated with the use of these farming practices.

An important benefit of using digestate is that being an organic fertilizer, it can improve soil structure, increase its fertility and enhance the ability to retain moisture. This can have a positive effect on the growth and development of plants, and therefore lead to a yield increase. In addition, it should be noted that the additional costs associated with the use of fertilizers, including digestate, pay off due to increased productivity and output. This means that the benefit (effect) from the use of fertilizers exceeds their cost, which makes this approach cost-effective for agricultural enterprises. However, it is important to emphasize that the efficiency of using digestate can vary depending on various factors, such as the type of crop, the growing conditions and the soil composition. Therefore, before implementing these farming practices, it is recommended to conduct a detailed analysis and determine the optimal rates of fertilizer application for each specific agricultural crop.

The conducted research enables us to undertake energy assessment of the technologies of growing corn for grain and vegetable crops.

Since the cost of traditional energy sources is growing and the volume of production of energy carriers available for agriculture is reducing, an extended introduction of economic equipment, energy and resource-saving technologies, non-traditional and constantly renewable energy sources under the condition of decreasing energy costs for the production of products is becoming relevant. The choice of the cultivation technology in each farm depends on the natural environmental conditions, the availability of agricultural machines, vehicles, storage facilities and financial and labor resources as well as energy costs (Boiko et al. 2010).

Research conducted by scientists from many countries have proven that under current conditions, saving of 1 ton of conventional fuel requires, as a rule, lower costs than the increase in extraction of its equivalent amount. Therefore, there is an urgent need to assess energy efficiency and determine directions for reducing energy costs for the production of agricultural products, since the increase of agricultural production efficiency imposes new requirements concerning both for the rational use of all resources and labor saving (Energy evaluation... 2004).

In conditions of a rather severe shortage of the resource potential, the energy assessment of developed technologies or their individual elements is important. Modern science-based technologies for growing agricultural crops, in particular corn for grain and root crops, should be energy-saving and rationally use both non-renewable and natural renewable energy, as well as ensuring the preservation of natural ecosystems (Palamarchuk and Kovalenko 2019; Vasiuta 2016).

With the help of market levers, the prices for resources are constantly changing (Lohosha et al. 2020). Economic evaluation of the proposed technology options cannot always objectively reflect the efficiency of the cultivation technology, therefore, accounting of the content of gross and exchangeable energy, comparing the income of energy accumulated in the yield with total energy spent on growing and harvesting (Lohosha et al. 2019).

The essence of bioenergy analysis is based on the fact that neither natural nor cost indicators of economic efficiency of growing corn for grain give an adequate idea of the permissible (normative) and actual level of total energy consumption for the full volume of mechanized work and human labor costs. Therefore, bioenergy evaluation of the researched cultivation technology elements is aimed at determining the payback of the costs of the total energy accumulated by the crop as well as identifying the level of energy intensity of the obtained products. All types of labor and technological costs are determined in energy units (equivalents), which reflect the amount of non-renewable energy as determined by kilocalories or joules. With the help of this indicator, technologies in crop production and agriculture are compared. In addition, bioenergy analysis provides a more complete assessment of individual elements of cultivation technology as it does not depend on the seasonal dynamics of prices for energy carriers, fertilizers, and the cost of final products (Palamarchuk and Kolisnyk 2022).

We assessed the energy efficiency of applying different nutritional backgrounds in the technologies of growing corn for grain and vegetable crops, namely carrot and red beet, based on the results of the above field experiment.

Analysis of energy consumption per 1 ha of corn grown for grain shows that the lowest values were observed in the control variant (without fertilizer application) – 47.3 GJ/ha. The highest consumption of total energy of 61.2 GJ/ha was observed in the variant where mineral fertilizer at the rate of $N_{90}P_{90}K_{90}$ and digestate-based bio-organic fertilizer "Efluent" (55.0 t/ha) were applied in the soil, which exceeded the control in terms of this indicator by 29.4% (Table 3).

TABLE 3. Energy efficiency of growing corn for grain and root crops depending on the fertilization system (average for 2019–2021)

TABELA 3. Efektywność energetyczna uprawy kukurydzy na rośliny zbożowe i okopowe w zależności od systemu nawożenia (średnia dla lat 2019–2021)

Crop	System of fertilization	Energy obtained with the yield, Ey [GJ/ha]	Energy consumption, Ec [GJ/ha]	Energy gain, Eg [GJ/ha]	Energy efficiency ratio, EER
Corn Kamponi CS	1*	99.12	47.29	51.83	2.10
	2	111.89	51.01	60.88	2.19
	3	146.01	54.03	91.98	2.70
	4	155.65	54.81	100.84	2.84
	5	158.37	55.12	103.25	2.87
	6	174.77	56.35	118.42	3.10
	7	188.01	61.21	126.81	3.07
	8	176.27	57.89	118.38	3.05
Carrot Bolivar F1	1*	70.98	58.34	12.64	1.22
	2	75.90	60.72	15.18	1.25
	3	85.63	62.48	23.15	1.37
	4	89.87	64.08	25.79	1.40
	5	92.32	65.59	26.73	1.41
	6	98.48	67.16	31.32	1.47
	7	108.59	77.27	31.32	1.41
	8	101.88	70.43	31.45	1.45
Red beet Kestrel F1	1*	125.71	75.71	49.99	1.66
	2	133.27	78.62	54.65	1.70
	3	145.30	81.60	63.70	1.78
	4	157.39	83.07	74,32	1.89
	5	165.73	85.26	80.47	1.94
	6	178.54	87.49	91.05	2.04
	7	199.43	99.96	99.47	2.00
	8	183.98	93.60	90.39	1.97

Note*: 1 – without fertilizers (control); 2 – application of water (45.0 m^3/ha); 3 – bioorganic fertilizer "Efluent" (25.0 t/ha); 4 – "Efluent" (35.0 t/ha); 5 – "Efluent" (45.0 t/h); 6 – "Efluent" (55.0 t/ha); 7 – "Efluent" (55.0 t/ha) + $N_{90}P_{90}K_{90}$; 8 – $N_{90}P_{90}K_{90}$.

Source: compiled on the basis of authors' research.

A similar situation was observed in the variants with vegetable crops. When the nutrition background increased, energy consumption also grew proportionally. Thus, in the variants of carrot cultivation, the highest energy consumption was observed on the sites where mineral fertilizer was applied in the soil at the rate of $N_{90}P_{90}K_{90}$ – 70.4 GJ/ha and combined with digestate (at the rate of 55.0 t/ha) – 77.3 GJ/ha, which was 12.1–18.9 GJ/ha more compared to the control (58.3 GJ/ha). The maximum energy consumption was observed when growing red beet. Thus, in non-fertilized variants, it amounted to 75.7–78.6 GJ/ha, while increased nutrition background led to the increase in energy consumption by 9.7–32.0 GJ/ha, depending on the form and rates of fertilizers.

Through analysis of the data given above, it can be concluded that the of fertilizers when growing grain and root crops leads to a significant increase in energy consumption. However, at the same time, this farming practice ensures a significant increase in energy obtained with the yield, gross energy gain and an increase in the energy efficiency ratio.

Thus, the studies have established that the application of the digestate-based bio-organic fertilizer "Efluent" ensured energy supply with the yield ranging within 146.0–188.0 GJ/ha, which was 47.3–89.7% more compared to the control in corn sowings, 89.9–108.6 GJ/ha or 26.6–53.0% in carrot sowings and 145.3–199.4 GJ/ha or 25.2–58.6% on experimental sites where red beet was sown depending on the application rate. Maximum indicators of gross energy output for the studied crops were observed in the variants where digestate was applied at the rate of 55.0 t/ha + $N_{90}P_{90}K_{90}$ (Variant 7 of the fertilization system).

Having calculated energy efficiency of the influence of fertilizers on the productivity of corn grain and the gross yield of root crops, we found that the greatest return was obtained in the variants where the digestate-based bio-organic fertilizer "Efluent" was applied in the soil at the rate of 55.0 t/ha. The highest indicators of the energy efficiency ratio were obtained in corn grown for grain – 3.10, in carrot – 1.47, and in red beet – 2.04.

In addition, high values of energy efficiency ratio were obtained in the variants in which mineral fertilizers were applied in the soil at the rate of $N_{90}P_{90}K_{90}$ and digestate-based bio-organic fertilizer "Efluent" (55.0 t/ha) + $N_{90}P_{90}K_{90}$. They were 3.05–3.07 for corn grown for grain, 1.41–1.45 for carrot, and 1.97–2.00 for red beet grown on the experimental sites.

Therefore, the application of mineral fertilizers and their combination with high rates of the digestate-based bio-organic fertilizer "Efluent" in corn and vegetable crops contributed to the yield increase, but at the same time, farming energy efficiency of fertilizers somewhat decreased, which contradicts the principles of the intensification of agricultural production.

In general, energy efficiency of the digestate-based bio-organic fertilizer "Efluent" applied directly under corn grown for grain, carrot and red beet is quite high, since the energy efficiency ratio significantly exceeded the unit, which indicates the energy efficiency of the crop cultivation technology that was studied. Rates of fertilizers that provide the highest energy yield under optimal costs should be applied ensuring compliance with the priority policy of energy conservation in agricultural production.

Conclusions

The cost of digestate can have a reasonable market value from 1.9 EUR/t from pulp and up to 21.4 EUR/t from bird droppings.

Indices of total energy consumption in the control variant (without fertilizer application) are 47.3 GJ/ha, the highest indices of 61.2 GJ/ha were found in the variant where mineral fertilizer at the rate of $N_{90}P_{90}K_{90}$ and digestate-based bio-organic fertilizer "Efluent" (55.0 t/ha) were applied in the soil in a complex manner. A similar situation was observed in the variants where vegetable crops were grown. Maximum energy consumption was observed when growing red beet. The application of digestate-based bioorganic fertilizer "Efluent" provided an increase in energy input with the yield for corn by 146.0–188.0 GJ/ha or 47.3–89.7%, carrot – 89.9–108.6 GJ/ha or 26.6–53.0%, and red beet – 145.3–199.4 GJ/ha or 25.2–58.6% compared to the control.

Based on the research results presented in this paper, the intensive technology of growing corn for grain and vegetable crops should be considered to be the most energy efficient, involving the application of the digestate-based bioorganic fertilizer "Efluent" in the soil at the rate of 55.0 t/ha, which ensured an energy efficiency ratio at the level of 3.10 (corn for grain), 1.47 (carrot) and 2.04 (red beet), which appeared to be 47.6, 20.5 and 22.9% more, respectively, compared to the control variants. High values of coefficients of energy efficiency were also observed in the variants with the simultaneous application of mineral fertilizers ($N_{90}P_{90}K_{90}$) and digestate-base bio-organic fertilizer "Efluent" (55.0 t/ha): on experimental sites of corn grown for grain – 3.05–3.07, carrot – 1.41-1.45, and red beet – 1.97–2.00, but the cost of these variants also appeared to be the highest.

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Zaawansowany europejski przegląd efektywności bioenergetycznej wykorzystania pofermentu z biogazowni podczas uprawy roślin rolniczych

Streszczenie

W artykule zwrócono uwagę na obliczenia wskaźników bioenergii podczas uprawy kukurydzy na rośliny zbożowe i warzywne na Ukrainie. Wyniki badań wskazują na korzyść ekonomiczną uprawy tych roślin dla wszystkich badanych wariantów. Z naszych analiz wynika, że wzrost efektywności bioenergetycznej produkcji tych roślin osiągany jest dzięki stosowaniu różnych dawek nawozów. Wzrost produktywności uzyskany w wyniku wdrożenia praktyk rolniczych przekracza dodatkowe koszty związane ze stosowaniem nawozów. Potwierdza to korzyść ekonomiczną wynikającą z uprawy tego typu upraw ze względu na zwiększoną efektywność bioenergetyczną osiągniętą poprzez optymalne zastosowanie nawozów. Przeprowadzone badania potwierdzają wysoką efektywność energetyczną badanego nawozu bioorganicznego (pofermentu) oraz energooszczędną technologię uprawy roślin. Wysokie wartości współczynników efektywności energetycznej zaobserwowano także w wariantach z jednoczesnym zastosowaniem nawozów mineralnych (N90P90K90) i nawozu bioorganicznego na bazie pofermentu „Ścieki" (55,0 t/ha) na obiektach doświadczalnych uprawy kukurydzy na ziarno (3,05–3,07), marchewki (1,41–1,45) i buraka ćwikłowego (1,97–2,00), ale koszt tych wariantów również okazał się najwyższy. W badaniach naukowych wykorzystano nowe metody i technologie efektywnego przetwarzania odchodów zwierzęcych w celu uzyskania nawozu organicznego, który z jednej strony można wykorzystać do poprawy żyzności gleby i zwiększenia plonów, a z drugiej do produkcji biogazu jako procesu energooszczędnego, który ma z drugiej strony znaczny potencjał wytwarzania ekologicznie czystej i odnawialnej energii. Zaproponowane podejście do osiągnięcia efektywności energetycznej pozwala na zwiększenie plonów bez zwiększania kosztów nawozów.

Słowa kluczowe: poferment, ścieki, bezpieczeństwo energetyczne, efektywność bioenergetyczna, współczynnik efektywności energetycznej