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Economic efficiency of using digestate from biogas plants in Ukraine when growing agricultural crops as a way of achieving the goals of the European Green Deal

Abstract: This paper presents calculations of the economic indicators of the researched elements of the cultivation technology of corn for grain and vegetable crops in Ukraine, which indicate that the cultivation of these crops is cost-effective in all variants of the experiment. The research has established that the increase in the economic efficiency of the production of these crops when applying different rates of fertilizers is achieved due to a more significant positive effect of the increase in productivity compared to additional costs associated with the use of these farming practices, while additional costs caused by the use of fertilizers are paid off many times over. It has been proven that the use of mineral fertilizers and their combination with high rates of bio-organic fertilizer (digestate) when growing agricultural crops helps to increase productivity. There have been further developed theoretical and practical provisions regarding the ecological problem of livestock waste disposal,

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in particular those of pig farms, and agricultural farms, i.e. the provision of organic fertilizers to ensure the yield increase as well as improvement in the quality of agricultural and vegetable crops, so as to make it possible to obtain high-quality products of plant and vegetable production during livestock waste disposal. The proposed approach to the economic assessment of technologies for growing corn for grain and red beet depending on the fertilization system makes it possible to increase the level of productivity of agricultural and vegetable crops with the effective use of bio-organic fertilizers in the modern conditions of sharp increases in the costs of mineral fertilizers.

Keywords: digestate, Effluent, energy security, energy efficiency

Introduction

The main goal of the modern economy and the bioeconomy is to achieve synergy between the economy, environment and society (Duque-Acevedo et al. 2020). Climate change and environmental degradation caused by the inefficient use of mineral nitrogen remain a global empirical problem. These challenges affect all sectors, including industry and energy, transport and agriculture, science, society and the environment. To cope with these challenges, the EU formulated a framework called "Green Deal" aimed to ensure a modern, resource-efficient and competitive economy where there are no significant greenhouse gas emissions by 2050 and where economic growth is decoupled from resource use (European Commission 2019).

The EU soil development strategy 2050 involves the use of bio-organic fertilizers (digestate) to improve soil fertility and agricultural efficiency, increase productivity in conditions of climate change, the circular economy, biodiversity and clean water resources, and increase carbon reserves in soil (European Commission 2021; Sabir et al. 2021).

Solving the problem of providing agricultural production with nitrogen is closely intertwined with the development of animal husbandry, which is the main source of traditional types of organic fertilizers. In addition, animal husbandry itself faces the problem of waste generation and disposal, and the protection of ecosystems and the environment, especially in conditions of global warming (Doyeni et al. 2022; Möller and Müller 2012; Directive 2008; BIS 2010; Gelaye et al. 2019).

To increase soil fertility and improve plant growth and development, it is necessary to apply organic and mineral fertilizers, implement optimal soil cultivation systems and increase humus content and soil moisture content (Clements and Bihn 2019). Reductions in the use of mineral fertilizers will lead to positive effects in terms of resource conservation, global warming and the preservation of soil quality (Alburquerque et al. 2012). To ensure intensive agricultural production and the full reproduction of humus reserves in Ukraine, it is necessary to apply around 350 million tons of organic fertilizers annually. Previously, this balance was maintained, mainly at the expense of domestic animal husbandry. However, the number of heads of cattle in Ukraine has decreased by more than 4.5 times over the past thirty years. Under modern conditions, there are more than ten times fewer heads of cattle per hectare of arable land in Ukraine than in the countries of Western Europe. In recent years, on average, twenty times less organic fertilizer than necessary was applied in agricultural and vegetable crops. As a result, the soil without organic substances became depleted, which lead to a decrease in the yield of agricultural crops. If this trend continues, then in the near future, Ukraine may be on the verge of an ecological disaster, a so-called humus famine. Under these conditions, no agrotechnical, reclamation, nature protection, organizational and economic measures would be able to restore the agrotechnical potential of land. In modern farming conditions in Ukraine, the real source of organic fertilizers is straw, stubble, stalks and other post-harvest residues, siderates, as well as livestock waste (manure) from keeping pigs, cattle and chickens; therefore, it is very important to determine the economic efficiency of their use.

1. Literature review

Recently, the demand for agricultural products has increased significantly due to the population growth and limited land resources. In the agrarian sector, the EU has paid special attention to the efficient management of livestock and crop production with various parameters of food production, environmental safety, waste disposal, energy production from food and non-food crops, soil use and greenhouse gas emissions. The EU is responsible for the regulation of the effective use of nitrogen (N) in animal husbandry, food production, organic and inorganic resources to increase yield, productivity and with less impact on the soil and the environment (Doyeni et al. 2021a; Reganold and Wachter 2016; Tittarelli 2020). Farmers have faced three challenges, in particular food security, farmers' profits and the preservation of a safe environment. To cope with these challenges, organic farming and adaptive and environmentally friendly technologies are being implemented. The use of digestates for soil fertilization is an important issue regarding this problem (Odlare et al. 2011; Abubaker et al. 2015; Doyeni et al. 2021b; Nkoa 2014; Irandoust 2016; Arthurson 2009; Gell et al. 2011).

The use of digestate is important for ensuring food security in organic production and increasing soil fertility and carbon fixation (FAO 2011). Digestate, compost, ash, biochar, mulch and green manure are good types of organic fertilizers that can positively affect soil fertility and have excellent characteristics regarding the content of the main nutrients (Makádi et al. 2016).

The digestate (fermented sludge) that remains in the bioreactor after obtaining biogas is an excellent substitute for organic fertilizer, and with its chemical composition it can completely restore the humus part of the fertile soil layer, but its cost is unjustified from the standpoint of the price of the nutrient chemical elements of which it is composed. It is known that during fermentation processes in the biogas reactor, about 30% of the organic substances are decomposed, thus the mass of the original substrate is reduced only by 3% after the end of the fermentation processes (Montemurro et al. 2008). Approximately 180 million tons of anaerobic digestate is produced annually in the EU, most of which is used as organic fertilizer (Corden et al. 2019).

There is no universally accepted single name for fermented sludge from a biogas plant. In domestic and foreign literature, it is defined in different terms: effluent, biofertilizer, bioorganic fertilizer, digestate, biogas sludge and biosludge (Palamarchuk and Krychkovskyi 2020; Macadi 2012; What is digestate? 2009). The digestate consists of the remains of fermented material and dead cells of microorganisms, and the digestate volume fluctuates at about 90–95% of the amount initially fed into the container (biogas plant) (Moeller and Stinner 2009). During the separation of sludge from the biogas plant, a solid fraction (aerated sludge) and a liquid (fugate) part are formed. These two parts of the digestate include the bioorganic fertilizer, which can be used immediately, both for basic fertilization and for the root nutrition of crops. Some authors suggest adding digestate-based biolimiting fertilizer to the main fertilizer and pre-sowing fertilizer (What is digestate? 2009). The use of digestate will ensure a decrease in the need for mineral fertilizers, which are commercially produced with a large use of fossil fuels and an increase in CO_2 emissions (Stewart et al. 2005; Timon et al. 2015; Popović et al. 2020). Considering the fact that most industrial biogas reactors have large volumes, the main problem of biofertilizers that will be obtained from a biogas plant is their storage and distribution.

Foreign researcher J. Abubaker claims that the use of digestate stimulates the growth of soil microorganisms and their metabolic activity (Abubaker et al. 2012). Digestate obtained from a biogas plant can increase crop yield by 10–30% compared to manure (Palamarchuk and Krychkovskyi 2020; Makádi et al. 2012). As a result of the conducted experiments, when the digestate from the biogas plant was applied, it was established that the yield of potatoes increased by 30%, the yield of perennial lawn grasses increased by three times, cabbage and tomato seedlings increased by 12–15%, and biomass in general increased by 30–50% (Datsko and Maistrenko 2012). The conducted studies showed high efficiency of digestate as an organic fertilizer in the technologies of growing watermelon and cauliflower (Alburquerque et al. 2012), kohlrabi (Lošák et al. 2016), alfalfa and spring wheat (Koszel et al. 2016), corn (Buligon et al. 2023), wheat (Doyeni et al. 2022; Doyeni et al. 2021a; Barłóg et al. 2019), tomatoes (Panuccio et al. 2021; Stoknes et al. 2018), lettuce (Kathijotes et al. 2015; Brtnicky et al. 2022), parsley (Pokhrel et al. 2018), sorghum (Rakascan et al. 2021), basil (Asp et al. 2022), garden crops (Restrepo et al. 2013), closed soil vegetables (Stewart et al. 2005; Stoknes 2020; Barzee et al. 2019; Liu et al. 2011; Lee et al. 2020), vegetables and other crops in non-soil systems on a digestate substrate (Restrepo et al. 2013; Stoknes 2018), open ground vegetables and mushrooms, especially when anaerobic fermentation is combined with hydroponics (Stoknes et al. 2016), etc., compared to traditional mineral and organic fertilizers.

Developing countries have a great interest in using biomass as a renewable energy source as their economy is mainly based on agriculture (Kirubakarana et al. 2009). Unfortunately, in Ukraine, the influence of organic fertilizers on the crop yield has not been thoroughly studied, so we have to rely on the data of scientists from Lithuania, Kazakhstan, France, the Czech Republic, Serbia, Latvia, Norway, Bulgaria, Spain, and England, where these technologies have been widely implemented.

In many countries of the world, the production and sale of organic fertilizers from a biogas plant is a very profitable business. The production cost of one liter of such fertilizer is a maximum of 10—15 cents if there is a drying and packing line, and the wholesale price on the domestic market is 1.0–1.5 US dollars (Makádi et al. 2016).

The sustainable development of agriculture requires the search for alternative sources of nutrients for plants and soil and maximum application. These sources should not be inferior to mineral fertilizers and should reduce the negative impact on the environment, including digestate (Lamolinara et al. 2022; Tambone et al. 2010; Lee et al. 2020).

Farmers' interest in the use of digestate is caused by the lack of a sufficient amount of organic fertilizers, the high cost of mineral fertilizers, the imbalance of organic matter in the soil, and the presence of a large amount of organic waste.

According to EU legislation, digestate can be classified into three categories: "organic soil improver", "growing medium" and "organic, non-microbial plant biostimulant", but not "organic fertilizers" (Stürmer et al. 2020). In Europe, digestates were previously classified as waste, and only a recent regulation of the European Commission has allowed to classify digestates as fertilizers (European Commission 2019).

This bioorganic fertilizer, in the form of gasified sludge from a biogas reactor, has a very useful property – it can reduce soil acidity due to a significant content of calcium and magnesium. Compared to mineral fertilizers, which are absorbed by 35–50%, bio-organic fertilizer is almost completely absorbed by the root system of plants. The value of such a fertilizer is based on the fact that nutrients are in organic form (Montemurro 2008; Palamarchuk and Krychkovskyi 2020).

Digestate (bioorganic fertilizers) is formed in the process of anaerobic fermentation of plant biomass and livestock waste, i.e. waste of agricultural production, which contains useful microflora when being stored but does not contain eggs and larvae of helminths, weed seeds.

Pig farms and industrial livestock farms can generate many wastes that are difficult to dispose of and pose risks to the environment if they are not properly processed and used (Zhang et al. 2017). An effective method of the practical solution of this problem is the processing of generated waste in a biogas plant to reduce the volume of waste and produce bioenergy (biogas) and digestate, which is used to increase crop yields and soil fertility (Seadi et al. 2012; Mata-Alvarez et al. 2014; Verdi et al. 2019; Alburquerque et al. 2012; Koszel and Lorencowicz 2015; Ayaz et al. 2021).

Digestate production in biogas plants is also possible due to the use of other raw materials (organic remains, chicken droppings, pulp, etc.). Thus, one ton of corn silage produces 780 kg of digestate, one ton of chicken manure provides 890 kg, one ton of manure – 910 kg, cattle manure – 920 kg, and pig manure – 990 kg. Every year 40–50 thousand tons of such digestate is produced per megawatt of biogas plant capacity.

2. Materials and methods

The research was conducted during 2019–2021 under the conditions of Organik-D LLC located in the right-bank Forest-Steppe of Ukraine. The trial field had gray forest soil with a mid-loamy mechanical composition, and the arable layer was 30 cm. The gray forest soil was characterized by the following agrochemical parameters: humus content (according to Tyurin) – 1.5%; nitrogen content – 9.6–14.3 mg/100 g of soil (according to Kornfield), mobile phosphorus – 7.5–13.9 and exchangeable potassium – 10.3–23.0 mg/100 g of soil (according to Chirikov).

The trial included three crops: corn hybrid – Kamponi CS (FAO 340), carrot hybrid – Bolivar F1 and red beet hybrid – Kestrel F_1, and a different fertilization system: control (without fertilizers and without irrigation), irrigation at the water rate of 25 t/ha, the application of bio-organic fertilizer "Efluent" (digestate) into the pre-sowing cultivation at the rate of 25; 35; 45 and 55 t/ha, the application of bioorganic fertilizer "Efluent" (digestate) at the rate of 55 t/ha + $N_{90}P_{90}K_{90}$ into the pre-sowing cultivation and the application of mineral fertilizers at the rate of $N_{90}P_{90}K_{90}$.

The agrochemical composition of pig manure was determined in the Prime Lab Tech laboratory, which is certified according to the ISO 22000 international certification, the valid state standards of Ukraine and methodical instructions. The microbiological analysis of organic fertilizer was performed in the biolaboratory "The Institute of Applied Biotechnological Transfer LLC".

Economic efficiency was calculated using technological maps of crop cultivation and taking into account all cost items (seeds, fertilizers, fuel and lubricants, pesticides, harvesting, etc.), which were accepted at the rates of 2021. Economic effectiveness of the use of bioorganic fertilizer "Efluent" based on the anaerobic fermentation of pig manure when growing corn, carrot and red beet as well as the processing of digital data were conducted in accordance with the guidelines (Kernasiuk 2010; Kovalenko et al. 2010; Zlobin and Kochubei 2003).

The anaerobic fermentation of manure is performed for fourteen days. The obtained bioorganic fertilizer "Efluent" is certified (TU U 20.1-38731462-001:2018) and patented in Ukraine.

Ecological, economic and energy efficiency of applying fertilizers was calculated according to the generally accepted methods (Kovalchuk 2002). Research data was processed by dispersion, correlation and regression methods of analysis according to Zhuchenko (1980) on a PC using special application programs for Windows, namely Excel and Statistica.

Nitrogen, phosphorus, potassium, and (for some plants) magnesium are the main chemical elements for which the availability in the fertile layer of soil increases the yield of grain, leguminous and industrial crops. Data on the cost of nutrients in widely used inorganic fertilizers – including urea, ammonium nitrate, ammonium sulphate, ammophos, diamophoska, nitroamophoska, superphosphate, urea ammonium nitrate (UAN-32) and potassium chloride – were selected from scientific and reference literature, summarized and analyzed. In these fertilizers, such nutrients as nitrogen, phosphorus, potassium and magnesium are in the form of salts, such as nitrates, phosphates, potassium, and magnesium. Taking into account the chemical formulas of fertilizer salts, the share of each of the elements was determined, and based on the price of the mineral fertilizer and the share of each of the constituent nutrients, the cost of each element was calculated.

Zakhariv (2019) determined the cost of nitrogen in mineral fertilizers, which are balanced by the content of constituent elements for various types of agricultural plants. The cost was UAH 26.68 per kg, including phosphorus – UAH 23.63 per kg, potassium – UAH 0.79 per kg, and magnesium – UAH 0.35 per kg. At the same time, based on the average NBU, the exchange rate of the Ukrainian hryvnia against the US dollar and the euro as of December 2019, the cost of each of the nutrient elements of the fertilizer was calculated in US dollars and euros. The cost of nitrogen in inorganic fertilizers was 1.05 euros, or 1.14 US dollars per kg, respectively, phosphorus – 0.93 euros, or 1.01 US dollars per kg, potassium – 0.72 euros, or 0.79 US dollars per kg, magnesium – 0.32 euros, or 1.35 US dollars per kg (Zakhariv 2019).

3. Results and discussion

We will determine the methodology and conditions of conducting research and the main methodological approaches that were used in determining the economic efficiency of the bio-organic fertilizer based on digestate.

Organic fertilizers used to improve fertility in agricultural enterprises of Tyvriv district of Vinnytsia region contain different amounts of nutrients depending on the different farms from which they originate. In our calculations, we used the organic fertilizer based on pig manure from the "Subekon" LLC pig complex, which has more than 12,000 fattening pigs as well as the organic fertilizer based on organic residues from the cultivation of corn, carrot, and red beet in the Sutyska village, Tyvriv district, Vinnytsia region, Ukraine.

The microbiological composition of litter-free pig manure used to obtain the bioorganic digestate-based fertilizer "Efluent" (Palamarchuk and Krychkovskyi 2020) is provided in Table 1.

Table 1. Quantitative composition of microorganisms in the liquid pig manure samples

Tabela 1. Skład ilościowy mikroorganizmów w płynnych próbkach gnojowicy świńskiej

No.	Type of pig manure	Total [thsd/g]	Including				Antagonist mushrooms		Toxin-producing mushroom species	
			pathogenic species		saprotrophic species					
			thsd/g	%	thsd/g	%	thsd/g	%	thsd/g	%
1	Unfermented	118.8	79.2	66.7	39.6	33.3	11.3	9.5	101.8	85.7
2	Fermented	193.8	12.6	6.4	181.2	93.6	6.2	3.2	31.2	16.1

Source: formed on the basis of authors' research.

The passage of pig manure through a biogas plant reduces the number of pathogenic microorganisms and increases the number of saprophytic organisms, which significantly improves the microbiological composition of the obtained digestate-based bioorganic fertilizer "Efluent" (Lohosha et al. 2022).

Analysis of the species composition of the pathogenic fungi of fermented and unfermented manure (Table 2) shows that the number of pathogenic fungi from the genus *Fusarium* decreased to 3.2% in fermented manure, while it was 9.5% in unfermented manure. In addition, there were no fungi of the genus *Aspergillus* in the fermented manure and their number amounted to 57.2% in unfermented manure.

Table 2. Genus ratio of pathogenic microflora in pig manure samples

Tabela 2. Stosunek rodzajowy mikroflory chorobotwórczej w próbkach obornika świńskiego

No	Variant	Total pathogenic fungi		Including genera [%]		
		thsd/g	%	Fusarium	Alternaria	Aspergillus
1	Unfermented	79.2	66.7	9.5	0	57.2
2	Fermented	12.6	6.4	3.2	3.2	0

Source: formed on the basis of authors' research.

When analyzing the species composition of saprotrophic fungi (Table 3), it is necessary to distinguish species from the genus *Penicillium* (*P. janczewskii* Zaleski, *P. raciborskii* Zaleski, *P. simplicissimum* (Oudem.) Thom, *P. chrysogenum* Thom) and from the genus *Acremonium (A. Kiliense* Grutz).

Table 3. Species ratio of saprotrophic microflora of pig manure samples

Tabela 3. Stosunek gatunkowy mikroflory saprotroficznej próbek obornika świńskiego

No	Variant	Total saprotrophic fungi		Including genera [%]	
		thsd/g soil	%	Penicillium	Acremonium
1	Unfermented	39.6	33.3	33.3	0
2	Fermented	181.2	93.6	87.1	6.5

Source: formed on the basis of authors' research.

The number of saprophytic fungi from the genus Penicillium in unfermented manure was 33.3%, while those from the genus Acremonium were not detected at all; in the fermented form their number increases and amounts to 87.1% in Penicillium and 6.5% in Acremonium.

When going of pig manure through a biogas plant decreases the number of pathogenic microorganisms and increases the number of saprophytic organisms, it significantly improves the microbiological composition of the "Efluent" bioorganic digestate-based fertilizer (Lohosha et al. 2022).

In addition to the microbiological composition, the agrochemical composition is important for the obtained fertilizer (Table 4).

Table 4. The results of the agrochemical analysis of the "Efluent" bioorganic digestate-based fertilizer (2019–2020)

Tabela 4. Wyniki analizy agrochemicznej bioorganicznego nawozu pofermentacyjnego „Efluent" (2019–2020)

No	Indicators, units of measurement	Trial results
1.	pH saline	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 absolutely dry matter [%]	0.60/34.5–37.3
5.	Content of organic matter in nature/in absolutely 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.	Sulphur in terms of SO_3 [kg/t]	0.54
11.	Magnesium in terms of MgO [kg/t]	0.42–0.52
12.	Calcium in terms of CaO [kg/t]	1.1–3.5
Microelements		
13.	Copper [mg/kg]	4.6–19.0
14.	Zinc [mg/kg]	32.0–43.0
15.	Manganese [mg/kg]	14.9–20.0
16.	Iron [mg/kg]	45.1–120.0
17.	Molybdenum [mg/kg]	0.23

Source: formed on the basis of authors' research.

The "Efluent" bioorganic digestate-based fertilizer is characterized by its alkaline reaction (pH_{saline} 8.5), high moisture content, which is 98.4% in the mass fraction, its significant content of nitrate nitrogen (18.2 mg/kg), copper (4.6 mg/kg), zinc (32 mg/kg), manganese (20 mg/kg) and iron (120 mg/kg). If the content of nutrients is converted in terms of the active substance per 1 ton of the "Efluent" bioorganic fertilizer, it contains 2.9 kg of nitrogen, 0.9 kg of phosphorus, 3.2 kg of potassium, 3.5 kg of calcium and 0.42 kg of magnesium. Therefore, the application of this fertilizer will provide plants with both macro- and microelements.

The need for nutrients, soil provision with macro- and microelements, research of the agrochemical microbiological composition of organic fertilizer were studied in accredited and certified laboratories. To correct the supply of plants with nutrients during the growing season, the functional method of leaf diagnostics was used with the help of the "Agrovector" PF-014 portable laboratory.

Data on the agrochemical composition and value indicators of organic fertilizers obtained from different types of animals are shown in Table 5.

TABLE 5. Calculation of the cost of biofertilizer from cow and pig manure with different dry matter contents

TABELA 5. Obliczenie kosztu bionawozu z obornika krowiego i świńskiego o różnej zawartości suchej masy

Basic nutrients	Nutrient content in biofertilizer [kg/t]	Cost of nutrients per ton of organic fertilizer [UAH/t]		
		€/t	$/t	UAH/t
Biofertilizer from pig manure (25% dry matter)				
Nitrogen	4.5	4.73	5.16	120.06
Phosphorus	5.6	5.21	5.67	132.33
Potassium	6.2	4.46	4.87	113.46
Magnesium	1.7	0.54	0.59	13.82
Total	18.0	24.88	16.29	379.67
Biofertilizer from cow manure (25% dry matter)				
Nitrogen	3.6	5.4	5.9	96.05
Phosphorus	2.8	2.6	2.84	66.16
Potassium	7.7	5.54	6.04	140.91
Magnesium	1.4	0.45	0.49	11.38
Total	15.5	13.99	15.27	314.50
Biofertilizer from pig manure (25% dry matter)				
Nitrogen	1.8	1.89	2.06	48.02
Phosphorus	2.4	2.23	2.43	56.71
Potassium	2.3	1.66	1.81	42.09
Magnesium	0.7	0.22	0.24	5.69
Total	7.2	6.0	6.54	152.51
Biofertilizer from cow manure (5% dry matter)				
Nitrogen	0.9	0.95	1.03	24.01
Phosphorus	1.2	1.12	1.22	28.36
Potassium	2.5	1.80	1.96	45.75
Magnesium	0.5	0.16	0.17	4.07
Total	5.1	4.03	4.38	102.19

Source: Zymovets 2007.

Pig manure, both liquid and thick, is characterized by a higher content of nitrogen, phosphorus and magnesium compared to cattle manure. However, a higher potassium content was found in cow manure compared to pig manure. Therefore, the use of biofertilizer based on liquid or settled pig manure is more relevant for the growth and development of the vegetative part of grain crops, while it is more appropriate to use biofertilizer based on cow manure to increase the yield of root crops and apply it to the soil in autumn. According to the results presented in Table 1, the thicker the biofertilizer's consistency is, the higher its cost will be. Thus, taking into account the cost of the constituent nutrients, 1 ton of thick biofertilizer (25% dry matter) from pig manure costs UAH 379.67, while 1 ton of thick biofertilizer from cow manure costs UAH 314.50, which can be used by farmers for sale on the agricultural product market. In addition, it is shown that the long-term storage of fresh manure in compost pits does not lead to a significant increase in price. In conditions of moisture losses of more than five times, the cost of biofertilizer from pig manure increases only 2.5 times, and the cost of biofertilizer from cow manure increases three times. According to the data presented in Table 5, the long-term storage of organic fertilizer based on pig and cow manure is unprofitable as it leads to significant losses of nitrogen (Zhuchenko 1980).

The obtained digestate from chicken droppings from the biogas plants of PJSC "MHP" had the following composition: liquid fraction (pH – 7.7–9.1 per cubic meter of total: nitrogen – 6.6 kg, phosphorus – 1.9 kg, potassium – 6.2 kg, manganese – 21 mg/kg, zinc – 8.2 mg/kg, copper – 14.1 mg/kg, cobalt – 7.2 mg/kg, sulfur in liquid – 0.27%); solid fraction (pH – 7.7–9.3. Total: nitrogen – 6.8 kg/t, phosphorus – 3.1 kg/t, potassium – 2.7 kg/t, manganese – 47.65 mg/kg, zinc – 12.5 mg/kg, copper – 34.5 mg/kg, cobalt – 18.1 mg/kg, sulfur in liquid – 1.56%). The digestate storage period is up to six months.

The introduction of the crop or growing technology into production should also be accompanied by economic justification in addition to productivity and product quality indicators. The selection of the economic options of technology that ensure the return of spent resources with maximum efficiency must be developed on the basis of the evaluation of research results and the analysis of the technological process elements. This will lead to improved product quality, increased production volumes, and reduced production costs (Zymovets 2007).

The final assessment of measures aimed at obtaining high yields and improving the quality of products is confirmed by their economic efficiency. Nowadays, none of the product manufacturers starts the development of new technologies without the reliable assessment of energy consumption and the calculation of economic indicators (Lupenko et al. 2012; Kovalchuk 2018).

Among the factors that determine the level of economic efficiency of growing vegetables and corn for grain, a significant position is held by innovative technological methods of their cultivation, which helps to realize their genetic potential more completely (Progressive technologies and standards of costs for growing vegetables 2012; Chernenko 2015; Parkhomets and Uniiat 2018).

Profitability is one of the main indicators characterizing the economic efficiency of production. The analysis of profitability indicators makes it possible to determine the types of products that are the most profitable for the production at the farm with the greatest opportunities for increasing the profitability of production. The higher the profitability of production, the more opportunities the farm has to make scientific and technical progress as well as the comprehensive intensification of agricultural production (Nepochatenko 2012).

The effectiveness of any technology for growing agricultural and vegetable crops must be confirmed by a positive result of the economic efficiency analysis (Lohosha et al. 2021). The economic assessment of the technological process of production makes it possible to identify specific opportunities for improving the efficiency of its operation with the help of certain techniques and methods, which include the following: economic analysis, index method, integral method, comparison method, expert evaluation method, correlation, regression, and cluster analyses. The economic analysis is intended for use directly at the enterprise and within its individual units. Consideration of economic characteristics enables establishing the influence of technical, technological, organizational and economic indicators, taking into account their impact on technical and economic indicators (Kabak 2018).

The energy analysis of modern agroecosystems shows that anthropogenic energy largely determines the productivity of agrophytocenoses. When analyzing the flows of this energy, it is necessary to take into account not only its costs for the cultivation of certain crops, but also the energy intensity of restoring soil fertility (Tarariko et al. 2001).

Technological processes of agricultural production are evaluated by a system of various indicators. Their comparison and generalization is impossible due to the use of different measurement units. International units of energy (calories or joules) can serve as single energy indicators for the analysis of the results of agricultural activity (Vozhehova et al. 2021; Kaletnik et al. 2021; Pryshliak et al. 2020).

The study of economic efficiency of crop cultivation was performed on the example of growing corn for grain and open ground vegetables.

Analysis of global experiences shows that high economic efficiency of growing crops, including corn and open ground vegetables, is achieved as a result of a rational combination of factors of production and placement, specialization, concentration, intensification and high marketability.

The availability of indicators of the economic assessment of crop cultivation makes it possible to evaluate and choose a more profitable variant of the technology and to outline the way to save resources and energy costs both in general by the technological flow and by individual components. Production methods ensuring an increase in output per unit of area under insufficient labor costs and resources are more cost-effective (Kamenshchuk 2020; Lohosha et al. 2018; Kaletnik et al. 2020; Tokarchuk et al. 2021).

Indicators of the economic assessment of crop cultivation enable choosing the most beneficial variant of the technology as well as the method of saving resources and energy both in terms of the technological process of cultivation as a whole and in terms of the efficiency of its individual elements.

In order to reveal the problem highlighted in the paper and to fulfil the tasks, the economic efficiency of growing corn for grain and open ground vegetables was calculated on the basis of data provided by the technological maps for each crop cultivated. The cost of fuel and lubricants, crop seeds, plant protection products, mineral fertilizers and “Efluent” bio-organic digestate-based fertilizer was calculated as of November 2021. The sale price of 1 ton of corn grain at the stock market at the time of the research was UAH 5,000, 1 ton of marketable carrot cost UAH 7,000, and those of red beet cost UAH 8,000, respectively.

The conducted economic analysis of technological methods of growing corn and open ground vegetables (carrots and red beet) showed that indicators of economic efficiency of producing commodity products, namely grain and root crops, were significantly affected by such a technological method of cultivation as fertilization. When it was applied as a separate factor, the following pattern was revealed: an increase in nutrition rates is followed by the growth of the amount and cost of additional products, conditionally net profit per hectare and, therefore, the level of profitability.

Calculation of the economic efficiency of growing vegetable crops including carrot and red beet under the application of different rates of fertilizers reveals that among the options studied, the maximum efficiency was ensured by the variants when “Efluent” bio-organic fertilizer was applied at the rate of 55.0 t/ha and the full application of bio-organic mineral fertilizer at the rate of 55.0 t/ha digestate + $N_{90}P_{90}K_{90}$ – these are variants 6 and 7 of the fertilization system.

In these variants, the increase in the root crop yield, compared to the control, was 22.0–29.2 t/ha in the case of growing carrot and 35.4–49.1 t/ha in the case of growing red beet. At the same time, production costs ranged within UAH 104,681.0–118,057 per ha and UAH 99,287.0–113,048.0 per ha, respectively. These fertilization variants provided a conditional net profit of UAH 251,059.0–288,293.0 per ha in the case of growing carrot and UAH 480,873.0–576,792.0 per ha in the case of growing red beet, the cost of 1 ton of root crops was UAH 2,030.0–2060.0 and UAH 1,310–1,370, and the level of profitability was 240–244 and 484–510%, respectively.

Thus, the analysis of economic indicators of the studied elements in the technology of growing corn for grain and vegetable crops in the conditions of the right bank Forest Steppe of Ukraine shows that the cultivation of these crops is profitable in all variants of the experiment.

In Ukraine, the Committee on Agrarian and Land Policy of the Verkhovna Rada has recommended the adoption of the European integration bill on improving state regulation in the field of handling pesticides and agrochemicals. One of the provisions of this draft law is to introduce the concept of “digestate of biogas plants” in the Law of Ukraine “On Pesticides and Agrochemicals”, and to cancel the legislative requirements for the state registration of digestate of biogas plants as an agrochemical (Draft Law of Ukraine of July 15, 2021). The draft law corresponds to the European legislation and practice of regulating the digestate handling in various EU countries. State registration of digestate as a fertilizer is not required either at the European level or at the level of individual EU countries. Additionally, there are both national and European digestate certification schemes for its compliance with accepted quality standards (Explanatory note to Draft Law of Ukraine of July 15, 2021):

- Belgium. The basic standards for the digestate production and use are represented in “Regulations on Waste and its Management” (VLAREMA). To monitor compliance with the standards, VLACO has been established, which is a certification body to control the quality of

Table 6. Economic evaluation of technologies of growing corn for grain, carrots and red beet depending on fertilization (average for 2019–2021)

Tabela 6. Ocena ekonomiczna technologii uprawy kukurydzy na ziarno, marchew i buraki czerwone w zależności od nawożenia (średnia z lat 2019–2021)

Crop	Fertilization	Yield [t/ha]	Production cost [UAH/ha]	Production costs [UAH./ha]	Conditional net profit [UAH/ha]	Cost price per ton [UAH/ha]	Profitability [%]
Corn Kamponi CS	1*	6.78	33,900	19,841	14,059	2,930	71
	2	7.65	38,267	20,086	18,181	2,620	91
	3	9.65	48,233	22,969	25,264	2,380	110
	4	10.28	51,417	24,133	27,284	2,350	113
	5	10.46	52,318	25,266	27,052	2,410	107
	6	11.55	57,733	26,459	31,274	2,290	118
	7	12.86	64,300	33,604	30,696	2,610	91
	8	12.06	60,283	29,254	31,029	2,430	106
Carrot Bolivar F1	1*	28.81	201,670	96,665	105,004	3,360	109
	2	34.22	239,540	97,084	142,456	2,840	147
	3	40.85	285,950	98,903	187,047	2,420	189
	4	44.24	309,680	100,902	208,778	2,280	207
	5	47.07	329,490	102,776	226,714	2,180	221
	6	50.82	355,740	104,681	251,059	2,060	240
	7	58.05	406,350	118,057	288,293	2,030	244
	8	51.45	360,150	110,138	250,012	2,140	227
Red beet Kestrel F1	1*	37.12	296,960	89,466	207,494	2,410	232
	2	40.34	322,720	89,978	232,742	2,230	259
	3	45.80	366,400	92,669	273,731	2,020	295
	4	53.22	425,760	94,946	330,814	1,780	348
	5	62.12	496,960	97,037	399,923	1,560	412
	6	72.52	580,160	99,287	480,873	1,370	484
	7	86.23	689,840	113,048	576,792	1,310	510
	8	73.01	584,080	105,869	478,210	1,450	452

Note*: 1 – without fertilizers (control); 2 – application of water (45.0 m^3/ha); 3 – "Efluent" biofertilizer (25.0 t/ha); 4 – "Efluent" (35.0 t/ha); 5 – "Efluent" (45.0 t/ha); 6 – "Efluent" (55.0 t/ha); 7 – "Efluent" (55.0 t/ha) + N90P90K90; 8 – N90P90K90.

The exchange rate of UAH to Euro is 28.0 to 1.

Source: formed on the bases of authors' research.

the standards of organic and biological waste processors. After the investigation, certificates of inspection of finished products are provided.

- Sweden. Digestate is subject to quality standard control according to the rules of Spcr 120 – "Regulations for certification of digestate from biowaste by the quality assurance system of Swedish waste management".
- Germany. Certification ("quality stamp") is provided by BGK (Bundesgtegemeinshaft Kompost), which is a professional independent association that certifies products for fertilizer manufacturers, statutory purpose of which is to control compliance with quality standards for processing household waste from households. The association bases its policy on the criteria established by the RAL Deutsche Quality and Control Institute. This "stamp" is mandatory for compost, digestate and the original mixture of sewage sludge composting. Digestate is mainly used as a fertilizer without preliminary treatment.

The effectiveness of bio-organic fertilizers (digestate) depends on various factors including climatic conditions, soil properties, digestate composition, types of agricultural crops and the period of application. Some authors indicated that the use of digestate resulted in a yield decrease compared to inorganic (mineral) fertilizers (Siebielec et al. 2018).

To improve the quality of digestate, it is often supplemented with additional components. In particular, some studies on the benefits of using livestock waste (pig manure) in combination with biochar and ash in comparison with mineral nitrogen fertilizers in agricultural production have been conducted (Kaletnik and Lutkovska 2020).

In general, based on the results of the analysis, it can be concluded that the increase in the economic efficiency of the production of corn for grain and vegetable crops when applying different rates of fertilizers is achieved due to a more significant positive impact of the increase in productivity compared to additional costs associated with the use of these agrotechnical measures; furthermore, additional costs caused by the use of fertilizers are paid off many times.

Conclusions

Based on the research results presented in this paper, it can be concluded that the use of organic fertilizers in modern technologies of growing corn for grain and open ground vegetables is an effective practice for obtaining additional products. When growing corn for grain, seed carrot and red beet, the most optimal economic effect was achieved when "Efluent" bioorganic digestate-based fertilizer was applied in the soil at the rate of 55.0 t/ha. When growing corn, this technique ensured a profit increase by UAH 17,215.0/ha with a profitability level of 118%, when growing carrot, it provided a profit increase by UAH 237,000.0/ha with a profitability level of 240%, and when growing red beet, it provided an increase by UAH 273,379.0/ha with a profitability level of 484%.

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Efektywność ekonomiczna wykorzystania pofermentu z biogazowni na Ukrainie przy uprawie roślin rolniczych jako sposób na osiągnięcie celów Europejskiego Zielonego Ładu

Streszczenie

W artykule przedstawiono obliczenia wskaźników ekonomicznych badanych elementów technologii uprawy kukurydzy na zboża i warzywa na Ukrainie, które wskazują, że uprawa tych roślin jest opłacalna we wszystkich wariantach doświadczenia. W badaniach ustalono, że wzrost efektywności ekonomicznej produkcji tych roślin przy zastosowaniu różnych dawek nawozów osiągany jest dzięki bardziej znaczącemu pozytywnemu efektowi wzrostu produktywności w porównaniu z dodatkowymi kosztami związanymi ze stosowaniem tych praktyk rolniczych, a dodatkowe koszty spowodowane stosowaniem nawozów zwracają się wielokrotnie. Udowodniono, że stosowanie nawozów mineralnych i ich łączenie z wysokimi dawkami nawozu bioorganicznego (pofermentu) przy uprawie roślin rolniczych sprzyja zwiększeniu produktywności. Dopracowano teoretyczne i praktyczne zapisy dotyczące ekologicznego problemu unieszkodliwiania odchodów zwierzęcych, w szczególności ferm trzody chlewnej i gospodarstw rolnych, tj. dostarczania nawozów organicznych zapewniających wzrost plonów oraz poprawę jakości zbiorów rolniczych, tak aby podczas utylizacji odpadów zwierzęcych możliwe było uzyskanie wysokiej jakości roślin i warzyw. Zaproponowane podejście do ekonomicznej oceny technologii uprawy kukurydzy na ziarno i buraka ćwikłowego w zależności od systemu nawożenia umożliwia zwiększenie poziomu produktywności upraw rolniczych i warzywniczych przy efektywnym wykorzystaniu nawozów bioorganicznych we współczesnych warunkach gwałtownego wzrostu kosztów nawozów mineralnych.

Słowa kluczowe: poferment, ścieki, bezpieczeństwo energetyczne, efektywność energetyczna