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Efficiency of Digestate from Biogas Plants for the Formation of Bio-Organic Technologies in Agriculture

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Abstract
The article examines the potential of digestate from biogas plants as a high-quality organic fertilizer that can ensure environmentally friendly development of the agro-industrial complex. The essence of the European Green Deal, the role of biogas production, and the use of digestate for achieving a climate neutral economy are considered. The purpose of the article was to analyze the potential of digestate production in Ukraine and to substantiate its role in Ukraine's achievement of the goals set by the European Green Deal. The research was carried out according to dialectical and systemic approaches, using monographic, economic-statistical, index, and cartographic methods. The results showed that Ukraine needs further development of biogas production and an increase in digestate production to meet the demand of agricultural enterprises for organic fertilizers, as there is currently an urgent need to increase soil fertility. It was determined that, in addition to European integration processes and the implementation of "green" technologies, a driving force for the intensification of digestate use is the high cost of mineral fertilizers on the Ukrainian and world markets, as well as high efficacy of digestate as an organic fertilizer. The authors proposed and calculated the green agriculture index, which is based on the calculation of the ratio of the amount of active substance, the rate of mineral fertilizers, kg to the rate of application of organic fertilizers, t/ha. Its levels (intensive, growing, declining, extensive) were determined by the regions of Ukraine, and strategies for the use of digestate were developed depending on the level of the region's greening. It was proven that the future of Ukrainian agriculture should be based on green agriculture and the active use of digestate as a fertilizer, which will help to produce environmentally friendly products, increase production volumes, and reduce the ecological burden on the environment. The use of digestate will help to achieve a reduction in the application of mineral fertilizers up to 25% by 2030 in accordance with the eco-goals of the European Green Deal.

Keywords: digestate, bio-organic technologies, fertilizers, biogas

1. Introduction

The European Green Deal is a roadmap to transforming the EU into an efficient, sustainable, and competitive economy, identifying the ways of transforming Europe into the world's first climate neutral continent by 2050, stimulating economic development, improving human health and quality of life, and transforming climate and environmental challenges into opportunities in all areas and policies of the EU, ensuring a fair and inclusive nature of the green transition.
The European Green Deal focuses on the clean energy, climate action, construction and renovation, sustainable industry, sustainable mobility, reduced environmental pollution, biodiversity, and sustainable agricultural policy (A Farm to Fork Strategy) (COM, 2020).
In 2020, business circles initiated internal debates regarding the European Green Course in Ukraine.

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The consequences of accelerated climate change encourage us to single out, first of all, the agricultural sphere from among the existing problems.
Therefore, the provisions for achieving eco-goals of the European Green Deal are fixed within the framework of the reform of the EU Common Agricultural Policy (CAP) and EU strategies on biodiversity and the Farm-to-Table approach. The strategy itself emphasizes that Farm-to-table is the main idea of the European Green Deal. The program is aimed at a comprehensive solution to the food system problems, and its key idea is the inextricable connection between healthy people, a healthy society, and a healthy planet.
At the same time, EU agriculture is still the only major system in the world that has reduced greenhouse gas emissions by 20% since 1990. However, even in the EU, this path was not linear and homogeneous. In addition, the production, processing, retailing, packaging, and transportation of food significantly pollute air, soil, and water. In general, this vector of work anchors this particular program in the general domain of the European Green Course.
The focus made by the EU agricultural policy on food security and reducing the impact of agriculture on the environment will dramatically increase the requirements of the EU member states for Ukrainian food exporters.
And this is a certain challenge for Ukraine, particularly for its agricultural exporters. In this regard, there is an urgent need to bring the agricultural sector of the economy into compliance with EU requirements. It is today when reorientation towards environmentally friendly agri-food production and the development of smart agriculture should be started. First of all, it is necessary to reduce the use of pesticides (by 25% by 2030) and mineral fertilizers (by 20% by 2030) in agriculture, as well as to ban the import of food products from the markets of the countries do not comply with EU legislation of environmental protection (COM, 2020).

2. Previous research

Implementation of the European Green Deal is developing rapidly, given numerous scientific investigations in this field. Kovalchuk, Kravchuk, 2019 show "green" transformations that are taking place in the agrarian sector, presenting the experience of Eastern partnership countries. Shpykuliak, Bilokinna, 2019 study "green" enterprises that play a crucial role in establishing an institutional framework for advancing alternative energy solutions within the agricultural sector of the economy. Bondarenko et al., 2023 study the significance of a "greeen" economy in fostering sustainable development, giving a comparative study of global and Ukrainian approaches.
Biogas production technologies occupy an important place among "green" technologies in agriculture and play a key role in the implementation of the European Green Deal. According to González R, Peña, Gómez, 2022 anaerobic digestion is considered to be the technology that plays an important role in building climate neutral economy due to the environmentally friendly treatment of waste.
Rekleitis et al., 2020 in their research fundamentally outline the functioning of an anaerobic biorefinery, wherein the anaerobic digester plays a pivotal role in converting raw materials into a range of intermediate and premium products. According to them, anaerobic digestation technology appears to be the most suitable choice for using the potential of

agricultural and livestock waste. Pryshliak et al, 2021 investigate the prospects of using biogas plants operating on crop and waste livestock from households stating that it is economically effisient, providing economic, ecological, social and energy effects.
Kuşçu, Çömlekçi, Çört, 2022 are focused on anaerobic disintegration of sewage sludge. Honcharuk et al., 2023 propose eco-friendly food waste management technology – anaerobic disintegration – that guarantees the responsible handling of food scraps and mitigates ecological contamination stemming from the release of treated wastewater into natural water systems. This approach not only curbs financial expenditures associated with environmental penalties but also presents opportunities to generate supplementary energy and income by marketing environmentally-conscious organic fertilizers crafted through controlled aerobic thermophilic biodegradation of organic resources.
Gaduš, Głowacka, 2018 are focused on using digestate to increase the yield of biomass, which will be used in the production of biogas.
The use of organic fertilizers is especially important for the agricultural sector of Ukraine, which is export-generating and needs special attention to increase production volumes to ensure food security both within the country and on a global scale. Kaletnik et al., 2020 examine the land circulation regulation in Ukraine and other counties and its influence on the soil condition. Ivanyshyn et al., 2021 confirm the importance of using fertilizers when growing cereals on the example of Ukraine in their research. Palamarchuk et al, 2020 study the advantages of application of organic fertilizers in the agricultural crop cultivation. Pantsyreva et al, 2023 focuse on bio-organic cultivation technology and the role of digestate while growing legumes.
Lohosha, Palamarchuk, Krychkovskyi, 2023 prove that the use of a combination of mineral fertilizers with high rates of bio-organic fertilizer (digestate from biogas plants) when growing crops helps to increase productivity and is of great importance for Ukrainian agriculture.
Anaerobic digestate from biogas plants is recognized worldwide for its beneficial fertilizer qualities (Lind et al., 2021). Stürmer et al, 2020 note that in accordance with the forthcoming EU Fertilizer Product Regulation, the inclusion of digestate as a permissible component aligns with the principles of the circular economy action plan.
According to Risberg et al., 2017, the utilization of digestate as a fertilizer not only facilitates the closing of the nutrient cycle but also diminishes the need for mineral fertilizers, which entail substantial inputs of raw materials and energy during production.
Issues of the development of biogas production and its use, taking into account the European Green Deal on the example of individual countries, remain insufficiently studied. This issue is especially relevant for Ukraine as an agrarian country having a great potential for biogas and digestate production and great needs both in its energy resources and organic fertilizers for agriculture.

3. Materials and methods

The research was based on the use of dialectical and systemic methods, which involved the study of the process of biogas and digestate production as a complex, multifaceted phenomenon. A monographic method was used to evaluate scientific views regarding the use of digestate as an organic fertilizer in the agrarian sector. The economic and statistical method was used when processing statistical data on the share of fertilizer costs in the structure of production costs of Ukrainian agricultural enterprises, analysis of applying mineral and organic fertilizers, and the use of pesticides in Ukraine. Tabular and graphic methods were used to visualize digital data. The use of the cartographic method for the scientific description and analysis of the capacities of biogas companies and digestate output at biogas complexes in Ukraine made it possible to clarify the leaders and outsiders among the regions. The authors used the index method to offer the green agriculture index, and its value was calculated for the regions of Ukraine with the determination of 4 levels of greening. The scenario-building method was used to develop strategies for the use of digestate within the region depending on the geen agriculture index.

The specified methods were used to achieve the goal of the study, namely to form an environmentally friendly approach to the agricultural sector operation in Ukraine based on the use of bio-organic technology of digestate application in order to increase soil fertility and crop yield.

The objectives of the research included: (1) substantiation of the role of biogas production and the use of digestate as a component of the European Green Deal, (2) the study of the prerequisites for the use of digestate in Ukraine through the analysis of the dynamics of the cost of mineral fertilizers, its impact on the overall growth of production costs in the agricultural sector of Ukraine's economy, (3) analysis of the current state of application of mineral and organic fertilizers in Ukraine and the compliance of these indicators with the goals of the EU Green Deal, (4) analysis of biogas production and digestate output at Ukrainian biogas complexes, (5) implementation of the environmental classification of the farming systems in Ukraine according to the rates of organic fertilizer application and the green index, as well as the development of scenarios for the use of digestate for the regions belonging to the same classification group.

4. Results and discussion

The key pillars of the European Green Deal are clean energy, climate action, construction and renovation, sustainable industry, sustainable mobility, reducing environmental pollution, biodiversity, and sustainable agrarian policy. Since Ukraine is an agrarian country, such areas as sustainable agricultural policy, climate action, and clean energy are especially important, and all this can be achieved by developing biogas technologies and using digestate as fertilizers.

There are many prerequisites for the development of production and use of biogas and digestate in Ukraine, in particular, there is a need for fertilizers at affordable prices.

According to the State Statistics Service of Ukraine, in the enterprises' structure of expenses for agricultural production (labor force, services), in 2020, expenses for mineral fertilizers amounted to UAH 60,290.1 million (13.7%), and farms spent UAH 14,805.8 million on the purchase of mineral fertilizers, and in the structure of production costs, their share was even higher (19.3%) (Figure 1).

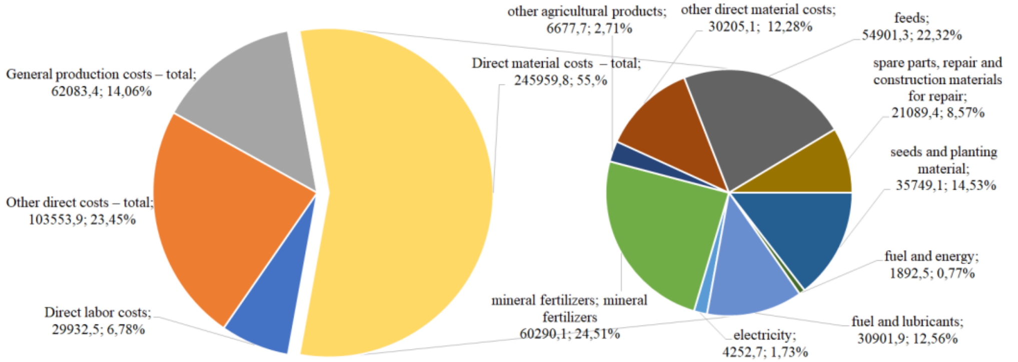

Figure 1. The structure of enterprises' expenses for agricultural production (labor force, services) in Ukraine in 2020, UAH million.
Source: (State Statistics Service of Ukraine, 2023)

A similar situation was observed in the agricultural enterprises in 2021, while their share in the structure of production costs tended to increase in 2022-2023 due to the deficit and rising prices for mineral fertilizers both on the world markets (Figure 2) and in Ukraine (Table 1).

Figure 2. Prices for mineral fertilzers on the world market
Source: (UkrAgroConsult, 2022)

Table 1. Prices for mineral fertilizers in Ukraine in 2021-2022, UAH/t

No	Type of fertilizer	September 2021		February 2022		May 2022		August 2022	
		min	max	min	max	min	max	min	max
1	Ammonium	14,000	15,500	26,500	26,500	26,500	27,200	30,000	31,000

	nitrate								
2	Carbamide	15,500	17,500	29,000	31,500	33,000	35,000	36,000	41,000
3	Potassium	15,000	15,500	19,500	20,500	25,000	27,000	40,000	43,000
4	Nitrogen, phosphorus, potassium (NPK 16:16:16)	17,000	18,500	22,000	24,500	27,000	29,000	36,500	39,000

Source: (UkrAgroConsult, 2022)

Application of mineral and organic fertilizers and humus content in Ukraine in 1990-2022 are shown in Figure 3.

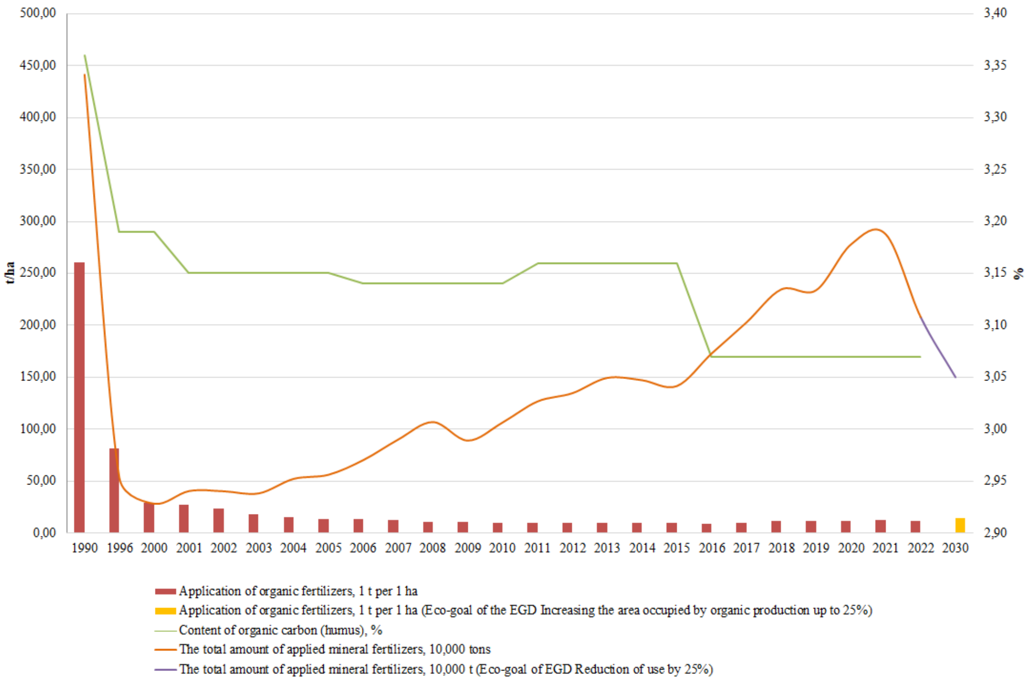

Figure 3. Application of mineral and organic fertilizers and humus content in Ukraine in 1990-2022 and compliance of these indicators with the goals of the EU Green Deal
Source: (State Statistics Service of Ukraine, 2023)

Having analyzed the data of Fig. 3, it is possible to come to a conclusion about a negative trend regarding compliance with the eco-goals of the European Green Deal since the volume of mineral fertilizers used by Ukrainian agricultural enterprises increased during 2017-2021, and due to the increase in the prices for mineral fertilizers in 2022, their volume slightly reduced. However, there can be observed an inversely proportional trend involving the application of organic fertilizers, the amount of which has been decreasing over the past 5 years.

To achieve the eco-goals of the EU Green Deal by 2030, it is necessary to substitute mineral fertilizers with organic ones in order to boost the growth of soil fertility and reduction of soil mineralization.

The expansion of biogas capacities is one of the options for increasing the volume of production of domesctic organic fertilizers in Ukraine.

According to the Bioenergy Association of Ukraine, in 2022 there were 61 enterprises operating in the field of biogas production in Ukraine, and their balance sheet included 50 biogas facilities with a total capacity of 127,219 MW, which provided electricity production at the level of 183,643 million kWh (Figure 4). The most powerful biogas plants were installed in Khmelnytskyi, Vinnytsia, Dnipropetrovsk, and Cherkasy regions.

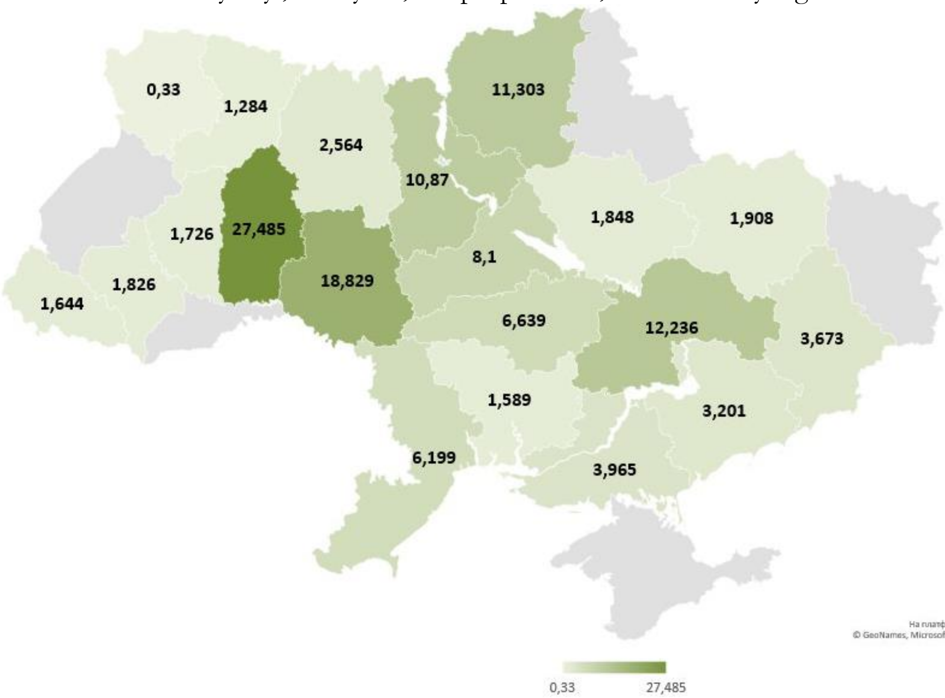

Figure 4. Capacities of biogas plants in Ukraine in 2022, MW
Source: (BAU, 2022)

In such biogas plants, biogas and digestate are formed during the reaction. Digestate produced in biogas plants is the remains of raw materials, by-products, and waste of animal or vegetable origin, in a mixture or not, formed as a result of a controlled process of anaerobic fermentation with the release of biogas.

Given the origin of the primary raw material of methanogenesis and the biological processes of its transformation, digestate is used as an alternative organic fertilizer and soil improver, which meets the requirements established by Regulation (EU) 2019/1009 of the European Parliament and the Council of 5 June 2019 laying down rules on the making fertilizing products available on the EU market and amending Regulations (EC) No. 1069/2009 and (EC) No. 1107/2009 and repealing Regulation (EC) No. 2003/2003 (UTC, 2023).

Neither at the level of the entire European Community, nor at the national level in individual countries of the European Union, official state registration of digestate as a fertilizer is required. The governments of these countries work according to national and European systems of digestate certification to verify compliance of its quality with approved standards. In Ukraine, an initiative was developed to solve this problem. This is a Draft Law on Amendments to the Law of Ukraine "On Pesticides and Agrochemicals" regarding state registration of digestate of biogas plants (Draft Law, 2021). This document proposes to make legislative changes to define the term "digestate", as this term is currently absent in Ukrainian legislation. The definition of "digestate of biogas plants" applies to the main mass of digestate, which is formed at operating biogas plants in Ukraine and is made from raw materials of agricultural origin. It can be: various types of manure, droppings, silage of agricultural crops, including corn, harvest residues, as well as primary or secondary by-products of food industry enterprises of plant origin (molasses, sugar beet pulp, bard, etc.).

According to the proposed draft law, mandatory state registration for digestate, which is produced by biogas plants and used as an organic fertilizer or soil improver, will be terminated. At the same time, it is necessary to comply with the requirements of current legal acts and sanitary standards. This initiative opens the possibility of importing digestate from biogas plants to Ukrainian fields without obstacles and contributes to improving the quality of soils in Ukraine. The draft law also provides for the Cabinet of Ministers of Ukraine to review and adapt the normative legal acts of ministries and other central executive bodies in accordance with this law and to adopt the necessary normative acts and documents for its implementation. First of all, to monitor compliance with digestate quality standards, as well as the implementation into Ukrainian legislation of the provisions of Regulation (EU) 2019/1009 of the European Parliament and of the Council dated June 5, 2019, which establishes the rules for placing fertilizers on the market.

Digestate output is not much less than the weight of biomass fed to the biogas plant. Thus, 780 kg of digestate is produced from 1 ton of corn silage, 890 kg is produced from 1 ton of chicken manure, 910 kg from 1 ton of pulp, 920 kg from cattle manure, and 990 kg from pig manure.

On average, 40,000-50,000 tons of digestate is produced per 1 MW of biogas plant capacity per year. Hence, all operating biogas plants in Ukraine (except Volyn and Kharkiv regions, which were not working in 2022) can produce approximately 5 million tons of digestate per year (Figure 5).

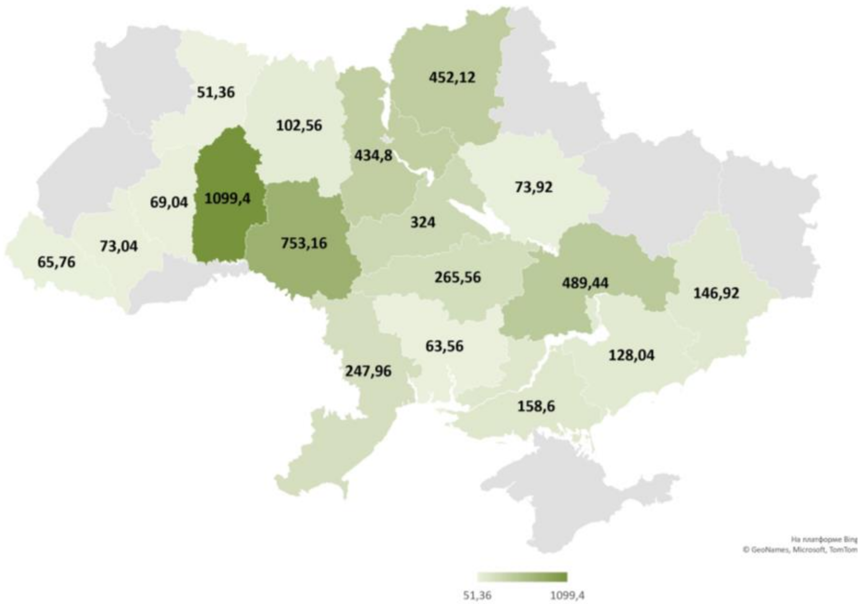

Figure 5. Digestate output at biogas plants in Ukraine in 2022, thousand tons
Source: calculated and formed by the authors

Digestate contains all macroelements (nitrogen, phosphorus, potassium, and calcium) and trace elements (copper, zinc, magnesium, boron, molybdenum, manganese, iron, and cobalt).
For example, 1 ton of digestate produced from chicken manure contains 15 kg of nitrogen, 6.6 kg of phosphorus, and 5.4 kg of potassium (this is the highest concentration of macroelements among all types of raw materials). Nitrogen proportion in the form available to plants is higher than in other fertilizers. Moreover, digestate contains 1-3% of organic carbon, including humic acids, which is valuable for restoring humus in the soil. In particular, the liquid fraction of digestate contains 0.21% of humic acids and 0.07% of fulvic acids, and the solid fraction contains 1.87 and 0.94%, respectively. In addition, the ratio between carbon and nitrogen in the digestate is 20:1 to 30:1, which is optimal for the soil. In addition, digestate also contains active bacteria that contribute to the decomposition of organic matter in the soil.
Depending on the input raw materials, 1 ton of digestate (from food waste) contains 103-129 kg of the active substance (NPK): nitrogen (N) – 20-22 kg; phosphorus (P) – 81-101 kg; potassium (K) – 2-6 kg. One ton of digestate (fertilizer) corresponds to 3.5-5.5 tons of litter manure in terms of active substance content, so the annual volume of digestate produced at biogas complexes in Ukraine can substitute more than 17 million tons of manure.
In countries where significant experience of biogas installations has been accumulated, technologies for the production of organic fertilizers from digestate are being actively developed. At first, digestate is divided into solid and liquid fractions. Further, the fertilizer production technologies are different. For example, ammonia is extracted from the liquid fraction, making ammonia water or ammonium sulfate. Or, after filtration, the magnesium-

containing struvite substance is precipitated, and then magnesium-ammonium-phosphate fertilizer is produced from it. The liquid fraction can be evaporated or filtered to obtain a concentrate that makes it profitable to transport the fertilizer over a distance of 40-50 km. In practice, thanks to evaporation, transport costs can be reduced by 70%. It is also possible to make a concentrated granulated organic fertilizer of prolonged action from the liquid fraction. Granular fertilizer is also made from the solid fraction. By the way, the pH of such fertilizers is optimal for the soil ranging from 6.8 to 7.5.

Fertilizer is convenient and easy to dose. Equipment for applying mineral fertilizers is suitable, does not require any preparation, and is completely ready to be used. Products can be supplied to the domestic, market and export.

The most straightforward method of utilizing "unprocessed" digestate as an organic fertilizer or soil enhancer involves directly applying it to the fields without any prior treatment. Nevertheless, these approaches come with several drawbacks and constraints, which is why they are not widely adopted. But there are disadvantages and limitations here: long-term storage of " unprocessed digestate increases the methane content; the content of large particles does not allow fertilizer to penetrate deep into the soil, a significant part of easily available nitrogen for plants is lost. Hence, it is recommended to treat "unprocessed" digestate at biogas facilities through the separation into solid and liquid fractions. In doing so, two distinct products are generated: a solid fraction with a dry matter content ranging from 20% to 40%, enriched with carbon and phosphorus, and a liquid fraction with a dry matter content of 1% to 8%, enriched with nitrogen and potassium. This separation offers the advantages of reducing the necessary storage tank capacity for digestate, minimizing methane emissions during storage, broadening the range of potential technical methods and application approaches for digestate in agriculture, and enabling further processing of both liquid and solid fractions.

Experiments on the use of digestate as a fertilizer have shown that it has an effect, and this effect is even higher than that of more traditional analogs. For example, in England, digestate (although from food waste) ensured an increase in the yield of winter cereals by 10% on average over 3 years, while green compost – by 7%, mixed compost (from green mass and food waste) – by 8%, manure by 9% and manure with straw by 10%. According to another experiment, applying 30 m^3/ha of digestate, each ton of which contained 3.6 kg of nitrogen, 1.7 kg of P_2O_5 and 4.4 kg of K_2O, made it possible to save on fertilizers.

There are successful cases of organizing biogas and digestate production in Ukraine. The largest biogas projects in Ukraine with a capacity of 10 to 20 MW cost approximately 2 to 2.5 thousand euros per 1 kWh. The main costs in such biogas projects, which are aimed at the simultaneous production of heat and electricity, include the costs of the power generating unit (30-40%), the construction of reactors and other technological facilities (35-45%) and technological equipment (15-25%). The payback on investment for biogas projects in Ukraine range from 5 to 6 years in favorable scenario and from 7 to 8 years in adverse scenario (UABIO, 2023).

In previous studies (Honcharuk, 2020), the biogas yield from various raw materials was calculated at Teofipol Energy Company LLC (Khmelnytskyi Region, Teofipol District, Teofipol Village) in 2020. It is estimated that the company can obtain a projected biogas yield of 9,262 m^3 from 1 ha of corn and 2033 m^3 of 1 ha of cereal straw, which can be used to meet one's own production needs, which allows for energy independence and production autonomy. Also, when selling the electricity produced by the enterprise under the green tariff (the projected output of electricity is 20228 kW from 1 ha of corn and 4441 kW from 1 ha of cereal straw), you can get a profit of EUR 1542.1 and EUR 445.2 (including VAT), respectively, from 1 ha of corn and cereal straws. As a result of the agrochemical analysis of digestate from biogas plants of Teofipol Energy Company LLC, it was established that it contains: nitrogen – 2570 mg/dm^3 in the liquid fraction and 9200 mg/dm^3 in the solid fraction; phosphorus – 5.3 and 1201.2 mg/kg, respectively, and potassium – 1963 and 3163 mg/kg.

At "Organik-D" LLC (Vinnytsia region, Vinnytsia district, Sutysky village), animal waste from the premises is poured into a biogas plant and fermented for 30 days. As a result of the operation of the biogas plant, the company receives: biogas output (1200 m^3/day); amount of electricity (250-300 kW) and thermal energy (300-350 kW); digestate of organic fertilizers (60 t/day). It was established that the application of organic fertilizers can have a positive effect on both yield and soil recovery. Thus, as a result of the conducted research, it was established that the yield of corn in the field with the use of digestate was 11.9 t/ha, and without the use of digestate – 9.6 t/ha, which is 2.3 t/ha less. In addition to the increase in corn yield in the field where digestate was used in combination with mineral fertilizers, the cost of purchasing fertilizers was significantly reduced by EUR 94.14/ha, compared to the field where only mineral fertilizers were used. The experiment proved that the use of digestate has a positive effect on the restoration of soil fertility, because in 1 year of its application at "Organik-D" LLC, the acidity of the soil changed from a slightly acidic level (5.4 pH) to a level close to neutral (6 pH) (Kaletnik et al., 2020).

As a result of research, when applying the liquid fraction of digestate from biogas plants as the main fertilizer at "Organik-D" LLC, "Theofipol Energy Company" LLC, Separate division "Biogas Ladyzhyn", "Vinnytsia Poultry Factory" LLC and PJSC "Oril-Leader", it was established, that according to the results of harvesting, the harvest increased to 30%. These enterprises are located in Vinnytsia, Khmelnytskyi and Dnipropetrovsk regions, Ukraine.

Therefore, the use of digestate (solid and liquid fractions) by agricultural enterprises as organic fertilizers in the fields will allow almost complete abandonment of the use of mineral fertilizers, and the harvest of agricultural crops will belong to the "Eco" category and will be sold at a higher price.

The ratio between organic and mineral fertilizers has a great influence on the intensity of humus formation in the soil.

According to research, if an increase in this ratio is higher than 1:15 (a ton of organic fertilizers per kilogram of the active substance of mineral fertilizers), it leads to the attenuation of the soil-forming process, slowing down of humification, and after reaching a ratio of 1:20 t/kg even to dehumification of soils (Honcharuk, 2020).

The reason for this effect is that almost all mineral fertilizers are salts of monovalent cations (K+, NH+, Na+), which disperse humus, move it along the soil profile, and it is decomposed by microbes faster. The application of organic fertilizers ensures the formation of organic colloids in the soil, which quenches the valence of monovalent cations and fixes them in the soil (AgroTimes, 2019).

The priority goal of the ecological farming system should be to optimize the application of organic fertilizers using their possible resources for this purpose, including manure,

composts, a non-marketable part of the biological harvest of cultivated crops, the mass of sidereal crops; soil protection system of tillage; environmentally justified system of plant protection from harmful organisms. In addition, an environmentally friendly farming system does not contrast natural resources with anthropogenic ones but makes the industry nature-conserving, symbiotic, and beneficial for both man and nature. The main tasks of green agriculture are the production of ecologically safe, economically justified products and the preservation and improvement of soil fertility.
In order to distinguish agricultural systems according to the level of their greening, their classification according to this feature is proposed (Table 2).

Table 2. Environmental classification of the farming systems according to the rates of fertilizer application and the green index

Levels of agriculture greening	Green agriculture index	Rates of organic fertilizers in the natural zones, t/ha					
		Dry steppe	Arid steppe	Steppe	Forest steppe	Right-bank Polissia	Western Polissia
The state of ecological agriculture							
Intensive	0-4	14	18	22	26	30	34
Growing	5-15	8-13	10-27	11-21	13-25	16-29	18-33
The state of declining greening of agriculture							
Declining	16-25	5-7	6-9	7-10	8-12	9-15	10-17
The state of chemicalization of agriculture							
Extensive	>25	4	5	6	7	8	9

Note: the green index is calculated by dividing the amount of the active substance, the rate of mineral fertilizers, kg, by the rate of application of organic fertilizers, t/ha
Source: calculated by the authors based on (Manko, 2008)

Having analyzed the estimated green index and the level of greening of agriculture in the regions of Ukraine in 2022 (Table 3), it can be concluded that in the Volyn, Zakarpattia, Zaporizhzhia, Odesa, and Lviv regions, the level of greening is extensive, which is extremely negative and proves the state of chemicalization of agriculture. A negative tendency towards the decline in greening of agriculture is also observed in the Rivne, Zhytomyr, Cherkasy, Dnipropetrovsk, and Chernivtsi regions. It is worth noting that no region of Ukraine reached an intensive level of greening of agriculture in 2022, which is an extremely threatening trend that does not contribute to the restoration of the soil humus.

Table 3. Calculation of the green index and level of greening of agriculture in Ukraine's regions in 2022

Regions	Amount of applied mineral fertilizers in the crop of the reporting year per 1 ha, kg	Amount of applied organic fertilizers in the crop of the reporting year, per 1 ha, t	Green agriculture index	Level of greening of agriculture
Volynsk	271	7.949	34.09233866	Extensive
Rivne	143	9.201	15.54178894	Declining
Mykolaiv	138	18.11	7.620099393	Growing
Zakarpattia	107	2.979	35.91809332	Extensive
Ternopil	236	21.191	11.13680336	Growing
Poltava	101	13.354	7.563276921	Growing
Kharkiv	101	13.708	7.367960315	Growing
Zhytomyr	154	9.183	16.7701187	Declining
Zaporizhzhia	105	3.325	31.57894737	Extensive
Donetsk	84	162.677	0.516360641	Intensive
Kherson	94	11.897	7.901151551	Growing
Odesa	94	2.134	44.04873477	Extensive
Kirovohrad	100	13.973	7.156659271	Growing
Cherkasy	174	8.657	20.09934157	Declining
Kyiv	143	17.628	8.112094395	Growing
Chernihiv	138	25.592	5.392310097	Growing
Dnipropetrovsk	125	7.262	17.21288901	Declining
Vinnytsia	214	16.176	13.22947577	Growing
Khmelnytskyi	147	14.546	10.10587103	Growing
Luhansk	81	-	-	-
Lviv	163	4.137	39.40053179	Extensive
Sumy	168	14.687	11.43868727	Growing
Chernivtsi	117	6.856	17.06534422	Declining
Total	3348	430.625	-	-

Source: calculated by the authors based on (State Statistics Service of Ukraine, 2023)

Table 4 presents the forecasted calculation of the green index and the level of greening of agriculture in the regions of Ukraine in 2022 using the potential of digestate as an organic fertilizer.

Table 4. Forecasted calculation of the green index and the level of greening of agriculture in Ukraine's regions in 2022 using the potential of digestate as an organic fertilizer

Regions	Electricity production at biogas plants, million kWh	Minimum output of digestate at biogas complexes (1 MW of biogas complex power = 40-50 thousand tons of digestate), t	Minimum output of litter manure (1 t of digestate = 3.5-5.5 t of litter manure by the content of active substance), t	Predicted green agriculture index, taking into account application of digestate	Predicted level of greening of agriculture
Volynsk	0	0	0	34.09234	Extensive
Rivne	1.632	51,360	179,760	0.00080	Intensive
Mykolaiv	0.274	63,560	222,460	0.00062	Intensive
Zakarpattia	1.192	65,760	230,160	0.00046	Intensive
Ternopil	3.839	69,040	241,640	0.00098	Intensive
Ivano-Frankivsk	5.043	73,040	255,640	0.00059	Intensive
Poltava	3.118	73,920	258,720	0.00039	Intensive
Kharkiv	0	0	0	7.36796	Growing
Zhytomyr	0.434	102,560	358,960	0.00043	Intensive
Zaporizhzhia	2.546	128,040	448,140	0.00023	Intensive
Donetsk	2.007	146,920	514,220	0.00016	Intensive
Kherson	5.77	158,600	555,100	0.00017	Intensive
Odesa	10.982	247,960	867,860	0.00011	Intensive
Kirovohrad	13.638	265,560	929,460	0.00011	Intensive
Cherkasy	15.92	324,000	1,134,000	0.00015	Intensive
Kyiv	11.349	434,800	1,521,800	9.39666	Growing
Chernihiv	17.862	452,120	1,582,420	8.72068	Growing
Dnipropetrovsk	13.123	493,040	1,725,640	7.24366	Growing
Vinnytsia	35.418	753,160	2,636,060	8.11813	Growing
Khmelnytskyi	39.496	1,099,400	3,847,900	3.82025	Intensive
Luhansk	0	0	0	-	-
Lviv	0	0	0	39.40053	Extensive
Sumy	0	0	0	11.43868	Growing
Chernivtsi	0	0	0	17.06534	Declining
Total	183.643	5,002,840	17,509,940	-	-

Source: calculated by the authors

The data calculated and shown in Table 4 convincingly prove that the use of digestate as an organic fertilizer when growing agricultural crops can ensure the achievement of the state of environmentally friendly agriculture in almost all regions of Ukraine, except for those that do not have operating biogas plants.

For areas in which digestate is not currently produced or is produced in limited quantities, it is proposed to purchase it and apply it to the soil for greening agriculture at the initial

stages.
Digestate handling scenarios aimed to equalize the level of greening within the regions of Ukraine are as follows:
- the regions with an intensive type of agricultural greening should sell excess digestate in solid form to the regions of the extensive and declining types;
- regions belonging to the growing type are recommended to use the existing potential of digestate production when growing agricultural crops to ensure an increase in soil fertility;
- regions belonging to the extensive and declining types have to increase biogas production capacity, which will result in an increase in digestate production for its use as a soil improver.
Thus, the use of digestate as an organic fertilizer will contribute to the introduction of bio-organic technologies for growing agricultural crops, which will contribute to the greening of agriculture and the achievement of eco-goals of the European Green Deal.
Prospects for the development of the biogas industry in Ukraine are related to the transition to the production and use of biomethane, which is purified biogas that corresponds to natural gas in terms of its energy properties and has a wider application. With further integration of Ukraine with the EU, large-scale use of digestate and expansion of organic farming in Ukraine is expected.

5. Conclusion

(1) Implementation of the European Green Deal requires a number of "green" events in various spheres of activity, and the agrarian sector occupies an important position among them. In particular, the eco-goals include reducing the use of fertilizers by 25% by 2023, increasing the production of organic products by 25%, as well as increasing the production of clean energy. To achieve them, the development of biogas technologies, which provide both energy resources and digestate, is important.
(2) Ukraine has joined the European Green Deal and is currently developing measures to achieve its eco-goals, including those related to the application of fertilizers. The analysis has shown that Ukraine is currently facing the problem of supplying agricultural producers with mineral fertilizers at affordable prices: their cost increases annually, which leads to an increase in this item of expenses in the structure of the enterprise's production costs (in 2020, the fourth of material costs of agricultural producers was made up of fertilizers, and after the sharp increase in the prices in 2022-2023, the share will keep on growing.
(3) Comparing the current state of fertilizer application in Ukraine with the eco-goals of the European Green Deal, the following trends can be observed:
- the amount of mineral fertilizers has been reduced in recent years, however, the rate of increase has not been fast enough to achieve eco-goals;
- the amount of organic fertilizers applied is dramatically low, which negatively affects soil quality indicators and leads to underachievement of potential output. This makes it impossible to achieve the eco-goal of producing 25% organic products.
(4) We consider the development of biogas technologies to be the most promising from the point of view of providing the agrarian sector with organic fertilizer. The analysis showed that biogas production is unevenly developed within Ukraine and raw material potential is not completely used. The conducted studies have shown that Khmelnytskyi,

Vinnytsia, Kyiv, Dnipropetrovsk, and Chernihiv regions are the leaders in digestate production at biogas plants.

(5) The Green Agriculture Index has been proposed to classify the regions into four types. The calculation based on the actual data of 2022 shows that one region belongs to the intensive type, five regions to the extensive type, 12 regions to the growing type, and five regions to the declining type (there are no data on the Luhansk region since data are not available due to temporary occupation). Under full use of the digestate potential as a fertilizer, the number of regions belonging to the intensive type is expected to increase to 14, and those of the growing type to six. Digestate management scenarios have been developed for the regions belonging to different classification groups depending on the level of greening of agriculture, which will accelerate the achievement of eco-goals of the European Green Deal.

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