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MARKET CIRCULATION OF DIGESTATE IN UKRAINE AND OTHER COUNTRIES*

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Abstract. The article examines the current state, characteristics and prospects of the market circulation of digestate, a by-product of anaerobic fermentation of biomass, which is a key element in the development of bioenergy and the circular economy. The chemical composition, agronomic value and classification of digestates depending on the type of raw material, aggregate state and degree of stabilisation are analysed. It is shown that digestate is an effective organic fertiliser capable of improving the physical and chemical properties of soils, promoting humus accumulation and restoring the microbiocenosis. Particular focus is given to the international experience of regulating digestate use in agriculture. The regulatory approaches of EU countries, Great Britain, China, the USA, Canada and Australia with regard to the safety, certification, logistics and agronomic monitoring of digestate-based fertilisers are analysed. The implementation of innovative technologies, such as digeponics, vermicomposting and microalgae cultivation, which enable the production of a wider range of value-added products, is emphasised. The need for further standardisation, infrastructure provision and incentive policies to develop the digestate market is emphasised. The potential environmental risks associated with the uncontrolled use of digestate are identified, in particular the eutrophication of water bodies and the accumulation of heavy metals. Statistical data on digestate production volumes in leading countries, including Germany, China, the United States and Ukraine, has been summarised. The key barriers to commercialising digestate are identified, and the strategic directions for integrating it into agricultural systems as a resource with high agronomic and economic potential are outlined. A comprehensive analysis of the current state, problems and prospects for the development of the digestate market in Ukraine in the context of the transition to a circular bioeconomy has been carried out. The agronomic value of digestate as a by-product of anaerobic fermentation, which can serve as an effective source of organic substances and macroelements for soil nutrition, has been revealed. The volumes of digestate production in Ukraine (1.5-2.0 million tonnes per year), the structure of its use, economic efficiency and factors affecting its market attractiveness have been assessed. Emphasis is placed on regulatory, technological, logistical and informational barriers that hinder the full development of the secondary market for biological fertilisers. The necessity for legislative recognition of digestate as an agrochemical product, the adaptation of national standards to European norms, the development of processing and certification infrastructure, and the creation of an information platform for market participants is substantiated. Mechanisms to stimulate demand, based on financial instruments and educational programmes for farmers, are also proposed. A scenario forecast for the development of the digestate market until 2030 is presented, considering the potential increase in its share of the organic fertiliser market from 8% to 22%. The scientific novelty of the work lies in the systematisation of international

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experience in regulating the digestate market, the adaptation of global practices to Ukrainian conditions, the assessment of the economic potential of digestate as a commodity product, and the formation of a forecast model for its integration into the agricultural sector of Ukraine.

Keywords: digestate, market circulation, market development forecasting, international standards, economic assessment, digestate market.

JEL Classification: Q16, Q28, Q42

1. Introduction

The modern model of sustainable agricultural development involves increasing production efficiency while minimising environmental impact, and establishing closed production and resource cycles based on the principles of the circular economy. In this context, the bioenergy sector, and in particular biogas production, deserves special attention, as it results in the formation of a by-product known as digestate.

The utilisation of digestate as a fertiliser is a prevalent practice in numerous countries worldwide, particularly those where biogas production is incorporated into agricultural systems.

Digestate, a by-product of anaerobic fermentation of organic matter, is a valuable agronomic resource that can be used as organic fertiliser, soil improver or raw material for further processing. Nevertheless, despite the product's considerable potential, its market circulation in Ukraine remains in its infancy. The absence of a definitive regulatory framework, inadequate infrastructure for logistics and storage, and the paucity of information available to farmers regarding the advantages of digestate are all factors that impede its commercialisation and systematic utilisation within the agricultural sector.

At the same time, in a number of EU countries, the United States, Canada, and some Asian countries, the digestate market is well established and actively functioning. There are quality standards, certification mechanisms, electronic trading platforms, and models for providing economic incentives to farmers and biogas companies. Studying these practices is essential for adapting them to Ukrainian realities, especially in the context of Ukraine's integration into the European market and the implementation of climate commitments in accordance with the European Green Deal.

Therefore, the relevance of researching the market circulation of digestate is determined by environmental, economic, technological, and regulatory factors. A systematic study of this process will allow for the development of effective policy tools for digestate management, increase its market value, and attract agribusiness to the circular development model.

The **purpose of this article** is to provide a comprehensive analysis of the market circulation of digestate in Ukraine and worldwide, and to identify key barriers and opportunities for the development of this market.

2. Literature Review

The composition and properties of digestate are largely determined by the type of input raw material (substrate) and the parameters of the anaerobic digestion process, in particular the residence time of the substrate in the reactor, the fermentation temperature regime and the intensity of biomass loading (Tambone et al., 2017). Digestate contains several forms of nitrogen, in particular ammonium nitrogen, which is readily available to plants, providing a rapid agronomic effect, especially when applied before the start of the growing season (Sipko & Ablieieva, 2024).

Integrating anaerobic fermentation with thermochemical technologies, particularly hydrothermal carbonisation, is a promising way to improve the efficiency of processing biomass. This approach optimises the use of organic waste and produces valuable hydrocarbon and biocarbon products, which have significant market potential as energy sources or soil conditioners in agriculture (Wei Wang et al., 2023).

The use of digestate as a fertiliser helps to reduce the environmental impact of organic waste while reducing agriculture's dependence on mineral fertilisers, which in turn supports the formation and development of a circular economy model (Ablieieva et al., 2022a; Palamarchuk et al., 2024). However, excessive use of digestate can pose environmental risks, such as nitrate leaching into groundwater and phosphorus accumulating in the soil. There is also the potential for organic pollutants, including pharmaceutical residues and pathogenic microorganisms, to spread (Akhiar et al., 2017).

The rational and effective management of digestate requires the creation and modernisation of the appropriate logistics infrastructure. This includes long-term storage systems, pumping and injection equipment for accurate application, and centralised composting sites to stabilise organic matter and reduce the risk of secondary contamination (Honcharuk et al., 2024).

Currently, digestate is not widely used as a complete fertiliser in Ukraine due to the lack of legally established status for this product, standardised quality standards, and an effective market mechanism for its sale and use (Gontaruk, 2024).

Research into the prospects for using digestate in Ukraine's green agriculture system indicates the need for further development of the biogas industry and

increased digestate production to meet the growing demand for organic fertilisers in the agricultural sector. In the context of forming a "green" index and forecasting trends until 2030, it has been established that the key determinants of intensified digestate use are along with the processes of European integration and greening of production, rising prices for mineral fertilisers on domestic and foreign markets, as well as the proven agronomic effectiveness of digestate as a source of nutrients and a means of restoring soil fertility (Honcharuk et al., 2024).

The economic potential of biomass, including agricultural waste and energy crops, is assessed by calculating the optimal volumes for processing into biofuel, taking into account the specific characteristics of individual types of resources. This approach involves setting restrictive parameters, in particular the minimum permissible areas of crops and livestock numbers required for the effective operation of existing biomass processing capacities (Galchynska, 2019; Lohosha et al., 2025; Kaletnik et al., 2025).

An example of an effective combination of digestate production, bioenergy and food production is the model of a production bioenergy cluster based on a sugar factory, which is based on the concept of increasing the energy self-sufficiency of Ukraine's agri-industrial complex. A key element of this model is the production of biogas through the anaerobic fermentation of by-products and organic waste, followed by the purification of the biogas obtained to biomethane, which is suitable for use as a high-quality energy fuel (Hontaruk et al., 2024; Kaletnik et al., 2020).

3. Materials and Methods

In the course of the study, a set of scientific methods was applied to ensure a thorough and well-founded examination of the issues surrounding the market circulation of digestate in Ukraine and abroad. In particular, the method of analysis and synthesis made it possible to determine the nature of digestate as a product of anaerobic fermentation, characterise its chemical composition, agronomic properties and potential as an organic fertiliser.

A comparative analysis method was used to study international experience and analyse approaches to the regulation, certification and use of digestate in the EU, the US, Canada, Japan and Switzerland. Economic modelling was employed to evaluate the effectiveness of using digestate in agricultural production, calculating potential benefits at farm and industry levels.

A statistical analysis was conducted to assess the present state and dynamics of the digestate market, encompassing its production volumes, consumption and potential sales niches. A SWOT analysis was conducted to identify both the internal reserves and limitations to the development of this market. This analysis revealed both the strengths and weaknesses of the market, as well as the external opportunities and threats for the introduction of digestate into agricultural practice in Ukraine. Furthermore, an expert survey was conducted among representatives of the agricultural business, scientists and relevant specialists, which facilitated the identification of key factors hindering the development of the digestate market, in particular regulatory gaps, imperfect logistics and low awareness among end consumers.

The scenario forecasting method was utilised to substantiate the long-term prospects for digestate use and to formulate a vision for the development of the relevant infrastructure. A forecast was made for the functioning of the digestate market in Ukraine until 2030. This was based on an analysis of current trends and possible scenarios for the development of the economic, regulatory and environmental environment.

4. Results and Discussion

Over the past decade, there has been a tripling of global biogas production, which has contributed, in part, to the replacement of fossil fuels. Concurrently, the anaerobic decomposition process, which constitutes the foundation of biogas production, is accompanied by the formation of a substantial amount of by-products – digestates. These digestates can be utilised in agriculture as organic fertilisers, thereby enhancing soil fertility and promoting carbon sequestration (Karimi et al., 2022).

Digestate is defined as a secondary product formed as a result of anaerobic fermentation of organic biomass under the influence of microorganisms in an oxygen-free environment. During this biochemical breakdown of organic matter, methane, carbon dioxide and residual mass in a liquid or solid state enriched with nutrients are generated. In global practice, digestate is increasingly viewed not as a by-product of biogas production, but as a valuable resource for the agricultural sector, requiring an appropriate regulatory framework, infrastructure and mechanisms for regulating its use.

Digestate is a semi-solid by-product formed during the anaerobic fermentation of organic materials. Its high content of essential mineral nutrients, such as nitrogen, phosphorus and potassium, as well as trace elements like zinc, copper, iron and molybdenum, makes it a valuable soil additive or biological fertiliser in agriculture (Palamarchuk et al., 2020; Doyeni et al., 2021; Lohosha et al., 2023). Digestate is constituted of a variety of organic and mineral components that determine its properties as a fertiliser for improving soil humus content, in particular macroelements (nitrogen, phosphorus, potassium), microelements (zinc, boron,

copper), organic substances (humic and fulvic acids), and residual biomass (cellulose, lignin).

There are several classifications of digestate: 1) by aggregate state: liquid, solid (granulated), paste-like; 2) by source of raw materials: digestate from livestock waste (manure, litter), plant biomass (silage, straw, pomace), food and household waste; 3) by degree of stabilisation: unstabilised, partially stabilised, stabilised.

The use of digestate has a positive effect on the agrophysical characteristics of the soil, stimulates its microbiological activity and contributes to the intensification of organic matter accumulation processes, which together increase the fertility of the soil environment (Möller & Müller, 2012).

The composition and physicochemical properties of digestate are determined by the characteristics of the raw material and the parameters of the anaerobic digestion process, in particular the duration of the material's stay in the reactor, the fermentation temperature regime, and the intensity of biomass loading (Tambone et al., 2017).

A significant step in this process is the hygienisation of digestate, particularly if it contains pathogens or is derived from municipal or food waste. In a number of countries, such thermal treatment is mandatory under environmental legislation (Sipko & Ablieieva, 2024).

Digestate, a by-product of the anaerobic processing of organic waste, is a mixture of microbial biomass, partially decomposed organic matter and inorganic compounds (Roopnarain & Adeleke, 2017). It is evident that digestate-based biofertilisers can be adapted for use on various agricultural crops, given the significant variability of its physicochemical properties and the degree of enrichment with microorganisms (Thomas & Singh, 2019). However, excessive or uncontrolled use of such fertilisers can cause environmental problems, including eutrophication of local aquatic ecosystems and accumulation of heavy metals in soils. At the same time, digestate is a promising resource for large-scale production of organic fertilisers, which is economically viable for both horticulture and large-scale agricultural production.

The production of digestate as an organic fertiliser is characterised by a relatively low cost compared to mineral fertilisers, as confirmed by studies by many authors (Lohosha et al., 2024; Lohosha et al., 2022). The use of fertilisers made from rainwater deserves special attention, as they have significant potential for increasing the efficiency of biofertiliser production. Due to their biodegradable nature, such fertilisers contribute to the activation of metabolic processes in microorganisms. In particular, composts, digestates and dehydrates based on rainwater contribute to the improvement of the agrochemical properties of soils, the restoration of the microbiocenosis and the reduction of anthropogenic pressure on the environment. Recent scientific developments indicate the possibility of enhancing the effectiveness of such fertilisers by enriching them with microorganisms that stimulate plant growth during biotransformation (Radawiec et al., 2023; Skrzypczak et al., 2023).

The contemporary effective utilisation of digestate necessitates a thorough analysis encompassing the characteristics of the raw material, processing technologies, economic considerations, the quality of the final product, the presence of impurities, as well as prevailing incentive policies and regulatory frameworks (Lamolinara et al., 2022). Concurrently, incentive policies and regulatory mechanisms that are designed to manage organic waste through anaerobic digestion and the production of digestate as a valuable product are establishing the conditions for economic benefits. However, the absence of state and industry quality certification systems currently hinders the commercialisation of digestate. To ensure the sustainable and safe use of digestate in various areas, the further development of technologies and the optimisation of technological processes are necessary. Additionally, incentives for its use, product quality regulation and increased social awareness are important factors supporting the commercial implementation of digestate. In this regard, further research is required to develop circular business models and standardise international norms for digestate-based products within the framework of the circular economy concept for organic waste.

However, improper use of digestate can lead to local pollution. In this context, EU countries have introduced standards based on the Nitrates Directive 91/676/EEC and REACH standards for the quality of organic fertilisers. In Germany, for example, digestate is subject to the Fertiliser Ordinance, which regulates application times, volumes and sample analysis (Sobhi et al., 2024).

In countries with a high level of digitalisation (Denmark, the Netherlands), there are electronic platforms for digestate logistics. They allow online coordination of transport, taking into account the agronomic needs of farms and optimising the use of fertilisers.

Thus, digestate plays a key role in the modern circular economy model within the agricultural sector. Its chemical properties make it a viable alternative to mineral fertilisers, and its environmental benefits strongly support the development of bioenergy technologies. However, effective use of digestate requires a regulatory framework, agronomic monitoring and appropriate infrastructure. The following section will examine practices around the world for regulating and stimulating the digestate market.

On a global scale, the biogas sector has achieved significant growth: according to the World Bioenergy Association, in 2021, biogas production amounted

to approximately 1.61 exajoules, of which about 50% was produced in Europe, 35% in Asia (mostly China), and 14% in the Americas. The volume of digestate production within the EU is estimated at 180 million tonnes per year, with Germany accounting for about half of this volume. The main use is direct application to soil as organic fertiliser, which closes nutrient cycles in agriculture (Sobhi et al., 2024).

Using digestate as a fertiliser is already common practice in many countries around the world, particularly in regions where biogas production is integrated into agricultural systems.

The objective of this study is to conduct research on the characteristics of digestate use in different countries, with a focus on approaches to its processing, standardisation, regulation and market introduction.

A survey of international best practice reveals a range of regulatory models reflecting the particularities of national policies on organic waste management and the management of anaerobic digestion by-products. Each country adapts its regulatory approaches in accordance with the level of development of bioenergy, environmental priorities and the economic feasibility of using digestate as a secondary resource.

The EU Regulation (EU 2019/1009) establishes safety requirements for fertilisers, including digestate. The Nitrates Directive (91/676/EEC) establishes limits on the permitted application of nitrogen, stipulating a maximum of 170 kg N/ha/year in the UK and 250 kg N/ha/year (EUR-Lex).

In Denmark, the operation of biogas plants is frequently characterised by a collaborative approach between farmers, a strategy that facilitates more efficient organisation of raw material logistics and digestate utilisation. The country provides state support not only for biogas production, but also for the use of digestate as fertiliser, in particular through tax breaks and subsidies for transport and processing.

The management of digestate quality is based on national standards developed by the Danish Biogas Association. Great attention is paid to the safety and hygiene of the product: when livestock waste is used, the digestate undergoes heat treatment or composting to reduce the pathogen load (Al Seadi et al., 2012).

Germany has established a regulatory framework encompassing input standards and chemical parameters, thereby establishing itself as a leader in the field of biogas energy in Europe, where the number of operational biogas plants exceeds 9,000. Within the German agricultural sector, digestate is utilised as a comprehensive organic fertiliser. The application of this product to the soil is subject to regulation in accordance with the provisions of the Fertiliser Ordinance (Düngeverordnung), a legislative instrument that governs the composition, frequency of application, and permissible emission limits for nitrogen and phosphorus (Bundestag beschließt Änderung des Düngegesetzes). In Germany, systems are employed for the separation of digestate into solid and liquid fractions, with each fraction subsequently utilised according to the requirements of the agricultural enterprise. The solid fraction is more frequently utilised on pastures or for crops with elevated organic requirements, while the liquid fraction is employed in irrigation systems. Digestate is also employed in the context of soil reclamation and forestry (Weiland, 2009).

Italy is developing the biogas sector in the context of its circular economy policy, which aims to maximise the reuse of resources. Digestate is used in the country not only in agriculture, but also in urban landscaping, vineyards, and as a component of compost. In Italy, it is common practice to certify digestate through independent laboratories, which provides consumers with guarantees of its quality and environmental safety. Technologies for granulating digestate are also being actively developed for ease of transport and sale through agricultural co-operatives (Tambone et al., 2009).

The United Kingdom certifies digestate quality based on the PAS 110 standard, and the nitrate vulnerability zone limits environmental risks (Sobhi et al., 2024).

In China, the new NY/T 2596 2022 standard sets limits for use in agriculture, but the commercialisation of digestate is still limited due to a complex regulatory framework (Lamolinara et al., 2022). The biogas programme became a national initiative back in the 2000s. Today, digestate is used in large-scale projects on rice fields, in greenhouses, and for restoring degraded land. Government subsidy programmes provide farmers with the means to collect and transport digestate.

Chinese studies have shown that digestate increases crop yields by 10-20% and reduces the use of mineral fertilisers. In addition, in some regions of China, digestate is used in aquaponics systems and as a source of humus formation in urban farms (Sobhi et al., 2024).

In the United States, digestate is mainly used on farms with biogas plants based on cattle manure. The Environmental Protection Agency has developed recommendations for its safe use. Some companies, such as *Regenis* and *DVO, Inc.*, are engaged in the commercial processing of digestate into granulated products.

In Canada, the Fertilizer Regulations CFIA contain requirements for the safety and effectiveness of fertilisers, including organic ones such as digestate. The market for organic fertilisers, including digestate, is particularly active in the province of Ontario. Digestate-based products for horticulture and greenhouse production are in high demand (Canadian Biogas Association, 2021).

In Australia, the current AS 4454 standard covers compost and treated organic waste, including digestate, providing for critical quality control.

Thus, different countries apply both general standards for organic fertilisers and specialised regulations specifically for digestate in order to ensure environmental safety and support the circular economy.

To ensure effective market circulation of digestate, it is important to have the following infrastructure:

1) storage capacity (up to 6 months);

2) transport vehicles (tanks, tankers with mixers);

3) applicators for soil application (disc, slit, injection);

4) composting sites (for digestate mixed with green waste);

5) drying units, granulators (for export/trade).

The majority of these installations are located in agricultural establishments, where there is a significant presence of livestock. These livestock are responsible for the generation of biogas, which is then utilised for various purposes. The Ministry of Environmental Protection has developed a set of recommendations for its implementation. It is evident that certain corporations, such as Regenis or DVO, Inc., engage in the commercial processing of data in the context of graphical user interfaces. This biotechnological transformation allows for the production of a wide range of products with high agronomic value, including biostimulants, phytohormones, protein hydrolysates, chitin, and other substances that increase plant stress resistance and promote their active growth (Mancuso et al., 2024).

The "digeponics" technology merits particular consideration as an innovative model of a closed production cycle, analogous to hydroponics, adapted to the conditions of digestate use. This technology has been incorporated as part of the European Union's environmental initiatives, with the objective of facilitating the effective integration of anaerobic digestion by-products, particularly digestate, carbon dioxide and thermal energy, for the purpose of cultivating vegetable crops in greenhouses. This approach has been demonstrated to increase greenhouse productivity, whilst also ensuring the rational use of resources in accordance with the principles of sustainable development.

Thus, the production of digestate has reached hundreds of millions of tonnes per year in countries with a developed biogas sector. Diverse legislation, ranging from European directives to national standards in countries such as China, Canada and Australia, defines the framework for the safe and effective use of digestate. Effective infrastructure solutions and methods for applying digestate are crucial for minimising losses and environmental risks. When applied correctly, digestate is highly efficient in terms of its agronomic value, but there is a risk of over-application and contamination. Technological advances in digestate processing present new opportunities for creating biostimulants and closing agricultural cycles.

The issue of determining the cost of digestate is one of the most complex and controversial in the context of its market circulation. Given that digestate is a relatively new product for many agricultural enterprises, there is a certain degree of caution regarding consumers' willingness to pay significant amounts for its purchase. Nevertheless, digestate has high agronomic potential, as it contains essential macronutrients and organic matter, which has a positive effect on the structural and physicochemical properties of the soil.

Biogas production in Europe was worth approximately 14.7 billion USD in 2024, with expected growth to 42.5 billion USD by 2034 (CAGR ≈11.2%) (Europe Anaerobic Digestion Market; Anaerobic Digestion Market).

In a global context, the distribution of anaerobic digestion plants is characterised by significant regional variation. For instance, Europe has over 18,700 biogas plants, with Germany being the clear leader with over 9,500 facilities processing more than 90 million tonnes of biomass each year. This scale indicates a high level of institutionalisation and public policy support for renewable energy and the circular economy.

North America is dominated by the United States, where more than 2,300 anaerobic digestion plants are in operation, while in Canada there are more than 140 such plants. The total processing volume is over 8.5 billion m^3 of biogas, which indicates the active implementation of organic waste utilisation technologies in the industrial and agricultural sectors.

China is the leader in the Asia-Pacific region, with over 5,000 biogas plants in operation and the capacity to process over 95 million tonnes of organic waste each year. Demonstrating rapid growth in the industry, India commissioned more than 320 new biogas plants in 2024 alone.

It is evident that there is a general global trend towards the growth of biogas production infrastructure, accompanied by an increase in demand for digestate as a by-product of these processes.

Digestate is produced on a large scale in the EU, with approximately 31 million tonnes of dry matter produced in 2022 and the potential to produce up to 177 million tonnes by 2050. According to the EBA, there was a 37% increase in methane production in 2024, which was accompanied by a corresponding increase in digestate production (Biogas Digestate in the EU: A Sustainable Resource).

According to data from the Bioenergy Association of Ukraine, there are at least 18 industrial biogas plants operating in Ukraine, producing 1.5-2.0 million tonnes of digestate per year (~5-10 m^3 per MWh of production) (Bioenergy Association of Ukraine).

As illustrated in Table 1, the estimated volumes of digestate production by region worldwide as of

2024 allow for an assessment of the scale of this by-product of anaerobic digestion, both in terms of its application as a raw material and its status as an environmentally significant secondary resource.

Table 1
Digestate production in countries around the world in 2024

Region	Biogas plants, thousand	Digestate production (million tonnes/year)
EU countries	~18,70	~31–180*
Germany (included)	> 9,50	a large proportion (~over 50%)
North America	~2,44	tens of millions of tonnes
(USA, Canada)	≥0,018	~1,5–2,0

Source: compiled by the author based on SAF data

In North America (the United States and Canada), with approximately 2,440 installations, the total volume of digestate amounts to tens of millions of tonnes per year, indicating significant potential for the reuse of organic residues in agriculture, especially in agro-industrial regions.

In Ukraine, despite the relatively small number of installations (18 biogas facilities), the volumes of product generated (1.5-2.0 million tonnes) are significant and indicate that there is a basis for further development of the secondary market for biological fertilisers.

Thus, the data obtained illustrate the growing role of digestate as an important element of the bioeconomy and outline the prospects for its market circulation both within individual countries and in a transnational context.

The assessment by the Biogas Association of Ukraine shows that the average equivalent cost of digestate can be 2-8 EUR/t depending on the raw material, while solid concentrate can cost around 17 EUR/t. For example, a mixture of pig manure and silage yields ~3.3 EUR/t, and the fractions yield ~2.3 EUR/t and ~17.1 EUR/t, respectively (Table 2).

Table 2
Economic assessment of digestate production from various types of raw materials in 2024

Raw materials	Composition	Equivalent value of digestate, EUR/t
Pig manure + silage	Whole product	~ 3,3
Solid fraction	Granules	~ 17,1
Liquid	Liquid form	~ 2,3

Source: compiled by the author based on data from the Bioenergy Association of Ukraine

The application of 30 m^3/ha of digestate has been calculated to result in an approximate saving of 109.6 EUR/ha on mineral fertilisers (~3.65 EUR/t). However, transportation costs (approximately 1 EUR/t for every 10 km for liquid, and approximately 2.7 EUR/t for the solid fraction) have the capacity to significantly mitigate the economic effect of delivery distance.

In the EU, approximately 73% of digestate is used directly as fertiliser, approximately 15% is used after processing (composting, granulation, etc.), and the remainder is used in other areas (horticulture, landfill cover, export).

Consequently, there has been a substantial increase in global digestate production, particularly in the EU, North America and Asia. In Ukraine, production is estimated at 1.5-2.0 million tonnes per year, which is significantly less than in EU countries, but with great potential for growth. The economic value of digestate is relatively low (~2-8 EUR/t), but its environmental value and potential savings on fertilisers can render it a competitive resource. The market attractiveness of a country is significantly affected by logistics, standardisation and product processing. Countries with developed certification systems and infrastructure benefit more from the sale and use of digestate.

In the context of the active introduction of biogas technologies in Ukraine's agricultural sector, digestate, as a valuable by-product of anaerobic digestion, is becoming increasingly important. However, despite the potential advantages of digestate market circulation in Ukraine, a number of objective and subjective barriers exist that hinder its full use in agriculture and other sectors.

One of the main problems is the lack of a clearly regulated legal status for digestate. As of 2024, digestate does not have a separate classification in Ukrainian legislation on organic fertilisers or waste. This creates a legal conflict: on the one hand, it is considered waste, and on the other, it is considered fertiliser. This situation complicates its transportation, storage and sale.

Ukraine currently lacks national standards for the physical and chemical properties of digestate, storage requirements, hygiene and safety of use. This complicates product certification and hinders export prospects. For comparison, the EU applies clear regulations, in particular: Regulation (EU) 2019/1009, which classifies recycled organic fertilisers; EoW (End of Waste) Framework, which determines when digestate loses its waste status and is recognised as a product.

Most Ukrainian farmers, especially small and medium-sized ones, do not have sufficient information about the agrochemical properties of digestate, how to use it, and the economic feasibility of its use. As a result, demand is limited and farmers are reluctant to take risks.

Transporting digestate, particularly in liquid form, is a costly logistical process that requires specialised vehicles. For many companies, delivering digestate over distances of more than 50 km is not economically

viable. Only a small proportion of biogas plants in Ukraine have systems for treating digestate, such as drying, granulation and composting. Absent this, the storage and commercialisation of digestate becomes challenging. Furthermore, the absence of laboratory oversight regarding N-P-K indicators, heavy metals, pathogen content, and other parameters hinders the assurance of product quality.

In contrast to the practices observed in the EU and the US, Ukraine lacks financial instruments to encourage the utilisation of organic fertilisers derived from digestate. In the Federal Republic of Germany, agriculturalists receive financial incentives in the form of subsidies for the utilisation of stabilised organic fertilisers. In Ukraine, however, farmers have no incentive to choose digestate if mineral fertilisers are available on credit or lease.

The successful introduction of digestate as a fertiliser in Ukraine requires an in-depth analysis of internal and external factors affecting its production, distribution and use, and the ability to make informed predictions about the development of this segment of the bioeconomy until 2030 (Table 3).

In the context of the current transformation of the agricultural sector and the transition to a circular economy, digestate is considered an important secondary resource that can not only increase the efficiency of agricultural production, but also contribute to reducing greenhouse gas emissions, replacing mineral fertilisers and improving soil cover. In this regard, determining the prospects for the development of the digestate market in Ukraine is becoming a key task for the state's agricultural and environmental policy.

According to estimates by the National Centre for the Circular Economy, in 2023, the annual potential for digestate production in Ukraine, assuming all biogas plants are operating at full capacity, will exceed 5 million tonnes (National Centre for the Circular Economy). However, the actual level of utilisation of the potential remains low due to a number of factors. These include the limited awareness among farmers of its agricultural properties, the absence of logistics infrastructure and the lack of mechanisms for market trading (Lohosha et al., 2020).

Regions with developed livestock farming and agro-industrial holdings that have access to modern biogas production technologies (e.g., Vinnytsia, Cherkasy, and Khmelnytskyi regions) demonstrated positive dynamics in the use of digestate. According to the State Agency for Energy Efficiency, from 2020 to 2024, the use of digestate as a fertiliser increased by 62%, indicating a gradual growth in confidence in this product among commodity producers.

One of the main problems in the use of digestate is the lack of a clearly defined legal status for this product. As of 2024, digestate in Ukraine is considered primarily as waste rather than as an agrochemical or secondary raw material. This significantly complicates its market circulation, reduces the attractiveness of investing in the relevant infrastructure, and hinders export potential.

The development of the digestate market in Ukraine has prerequisites both on the supply side (growth in the number of biogas plants) and on the demand side (agricultural producers' need for cheap, affordable fertilisers). At the same time, further market development requires a comprehensive approach aimed at addressing regulatory, technological, informational and market issues.

Firstly, it is important to note that the regulatory framework for the utilisation of digestate in Ukraine is in its nascent stages. A re-evaluation of national regulations is necessary to align with EU practices, which acknowledge digestate as a product suitable for soil application, contingent on the fulfillment of environmental and safety requirements. In Ukraine, the legal status of digestate is not clearly defined. It is not classified as either organic fertiliser or waste, creating regulatory uncertainty. This, in turn, hinders market development, particularly in terms of certification, transportation, sales, and agrochemical regulation. Unlike many EU countries where digestate is clearly regulated (e.g., Germany, Austria, Italy), Ukraine needs to adopt specialised standards or at least adapt existing ones to European norms, in particular EN 16086, EN 15934, as well as the recommendations of the European Biogas Association (EBA).

Secondly, the technological characteristics of digestate as a product with a high moisture content

Table 3
SWOT analysis of the digestate market in Ukraine

Strengths	Weaknesses
- High agronomic potential of digestate as an organic fertiliser. - Availability of biogas plants that generate digestate. - Increase in mineral fertiliser costs.	- Lack of a clear legal framework for the classification and regulation of digestate use. - Insufficient awareness among farmers about the properties of the product. - Limited infrastructure for transporting and storing digestate.
Opportunities	**Threats**
- European policy on developing a circular economy. - Potential for export to other Eastern European countries. - Financial support from international environmental funds.	- Competition from manufacturers of traditional mineral fertilisers. - Environmental risks associated with improper use of digestate. - High cost of initial analysis and product certification.

Source: authors' research

and low nutrient density present challenges in terms of transportation, storage and application. Market development is only possible if systems for the local or regional use of digestate are created in close proximity to biogas plants. This requires logistics schemes to be implemented at the level of agricultural clusters or co-operatives, in which biogas operators and farmers interact within a "resource-production-use" framework.

In addition, farmers' awareness of digestate as an effective fertiliser is low. Most agricultural producers do not have a clear understanding of the chemical composition of digestate, its properties, application possibilities, application timing and potential economic efficiency. That is why it is necessary to develop educational and demonstration programmes, conduct field trials, and support scientific institutions that study the impact of digestate on crop yields, product quality, soil condition, and greenhouse gas emissions.

Another aspect that must be considered is market-related. Notwithstanding the auspicious outlook, the digestate market in Ukraine has yet to be consolidated as a segment characterised by transparency in pricing, standards, consumer base and supply. The majority of digestate is retained by biogas producers for on-site use, or alternatively transferred to agricultural producers free of charge. In order to activate this market, it is necessary to establish an information platform that includes a register of digestate producers and consumers, as well as samples of standard contracts, transportation cost calculations, and recommendations for application.

Another significant factor for development is the attraction of investment and state support. The promotion of the acquisition of equipment for the processing and granulating of digestate, the augmentation of agro-ecological programmes (notably, the provision of compensation for the preservation of soil fertility), and the implementation of tax incentives for market participants have the potential to provide a positive stimulus to the large-scale dissemination of digestate utilisation practices.

In the long term, the digestate market could become an important element of the "green transformation" of Ukraine's agricultural sector. Increasing the level of organic matter in soils, reducing the use of chemical fertilisers, reducing CO_2 and methane emissions, and improving energy efficiency are all in line with Ukraine's Low Carbon Development Strategy to 2050 and the objectives of the European Green Deal.

Given the current trends towards environmentally friendly farming and resource-efficient production, as well as the growing popularity of bioenergy, positive growth in Ukraine's digestate market can be expected. If the right regulatory environment is created, government incentives are introduced and environmental awareness among farmers increases, the market could achieve significant growth by 2030 (see Table 4).

According to forecasts, a significant increase in digestate production is expected by 2030. At the same time, the share of digestate used as fertiliser will also grow, indicating the gradual integration of digestate into the organic farming system. The expansion of digestate use as a fertiliser will be accompanied by an increase in the area of agricultural land on which it is used. The share of digestate in the overall structure of organic fertilisers will increase from 8% to 22%, which indicates its growing role as a source of biologically active elements in soil nutrition. There is also a positive trend in the development of the domestic digestate market, confirming its economic potential and prospects as a commercial product in the agricultural sector.

Thus, the projected development scenario indicates the promising prospects for the digestate market in Ukraine, provided that institutional support, investment in research and training for farmers continue.

5. Conclusions

This article provides a comprehensive analysis of the current state of the digestate market in Ukraine, the problems it faces, and its prospects for development in the context of transitioning to a circular bioeconomy. It substantiates the economic feasibility of using digestate as a secondary resource in agriculture.

As a predominantly agricultural country, Ukraine has significant potential to develop the digestate market. However, the current situation indicates the existence of structural, legal and informational barriers. Overcoming these challenges requires legislative regulation of digestate status, the introduction of standards and technical conditions, the development of information and training programmes for farmers, the creation of

Table 4
Key forecast parameters for the development of the digestate market until 2030

Indicator	2024	2026 (forecast)	2028 (forecast)	2030 (forecast)
Digestate production volume, thousand tonnes	620	910	1 280	1 640
Percentage of digestate used as fertiliser, %	42	56	68	75
Area of land treated with digestate, thousand hectares	48	71	103	138
Share in the structure of organic fertilisers, %	8	12	17	22
Annual volume of the domestic digestate market, million UAH	186	274	397	523

Source: authors' research

support systems for digestate processing and use, and the stimulation of demand through financial instruments.

In the context of growing biogas production, the prospects for developing the domestic digestate market are outlined, particularly through expanding bioenergy plant systems and integrating sustainable farming principles. Based on international experience, recommendations are made for aligning national legislation with EU standards, particularly with regard to the classification, certification and labelling of digestate. A forecast model has been developed to predict the development of the digestate market in Ukraine until 2030. It predicts that its share of the organic fertiliser market will increase from 8% to 22%.

The research's scientific novelty lies in its integration of economic, regulatory and environmental a pproaches when assessing the digestate market. It also identifies the institutional and legal prerequisites for establishing an effective mechanism for its market circulation.

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