ISSN-L 2664-9969; E-ISSN 2706-5448

UDC 338.43:005.35:502.131.1
JEL Classification: Q01, Q56, Q16, M14, C55
DOI: 10.15587/2706-5448.2026.357883

Oleh Kniaz,
Petro Pererva,
Nelli Heorhiadi,
Roksolana Vilhutska,
Khrystyna Peredalo

FORMATION OF AN ESG MANAGEMENT SYSTEM BASED ON DIGITAL ANALYTICS

The object of research is the process of forming an ESG management system based on digital analytics (DA). The research addresses the issue of implementing value-based sustainable development guidelines in the agricultural sector through ESG-oriented resource management mechanisms using DA tools. The theoretical and applied parts of the research are based on a combination of a systemic vision of the problem under study, analytical procedures, comparative analysis, and economic-mathematical tools. The empirical basis of the research was formed through the analysis of data for 2020–2024. The research incorporates reports of agri-food companies, materials from international institutions, as well as EU documents regulating digitalization in food supply chains. On this basis, an economic and statistical analysis was conducted to assess the role of DA in shaping the ESG management system in the agricultural sector. Economic and mathematical modeling was applied to identify relationships between the efficiency of resource use by enterprises and their performance according to ESG criteria. The obtained results made it possible to establish that, in the process of forming ESG-oriented management, DA can serve as an important tool for transforming primary information on the use of natural resources into a system of measurable ESG indicators. Such indicators can be used both in internal enterprise management and during auditing or comparison of performance results across different periods. The model developed in the research was tested using data from the agricultural sector of Ukraine. The results of its application confirmed the existence of a stable relationship between the level of resource efficiency in production, economic performance, and environmental parameters included in the ESG framework.

Keywords: *sustainable development, agricultural sector, ESG management, digital analytics, CSRD.*

Received: 16.02.2026
Received in revised form: 05.04.2026
Accepted: 16.04.2026
Published: 30.04.2026

How to cite
Kniaz, O., Pererva, P., Heorhiadi, N., Vilhutska, R., Peredalo, K. (2026). Formation of an ESG management system based on digital analytics. Technology Audit and Production Reserves, 2 (4 (88)), 98–111. https://doi.org/10.15587/2706-5448.2026.357883

1. Introduction

Providing people with food largely depends on how the agricultural sector works. Agriculture uses large amounts of natural resources. This primarily concerns land, water and energy. The way these resources are used affects the state of the environment, living conditions in villages and the economic situation in the regions.

In recent years, the working conditions of agricultural enterprises have been changing noticeably. This is influenced by climate change, gradual depletion of soils, and the increase in the cost of energy carriers. Additional difficulties are created by the instability of international markets and logistics. Because of this, enterprises are forced to reconsider their approaches to resource management. It becomes clear that the economic results of production can no longer be considered separately from the environmental consequences of activities and the social responsibility of business.

The concept of sustainable development is increasingly mentioned in scientific research. It involves combining the economic interests of enterprises with the preservation of the natural environment and taking into account the needs of society. For the agricultural sector, this means changing approaches to assessing the results of enterprise activities. Now, along with financial indicators, attention is paid to how natural resources are used and what impact production has on the environment. In this regard, ESG approaches have become widespread. They combine environmental, social and management aspects of enterprise activities.

For agricultural enterprises, this means a gradual transition to the coordinated use of land, water, energy and biological resources. In practice, the implementation of this idea turns out to be much more difficult than it might seem at first glance. Different farms use different data accounting systems. Some information is not used at all when making management decisions. This creates difficulties in assessing the efficiency of resource use and their impact on the results of enterprise activities.

The development of digital technologies in agriculture plays a significant role in the transformation of these processes. In modern conditions, sensor systems, platforms for accounting of production processes and analytical tools are increasingly used. The information obtained using these systems does not guarantee an increase in management efficiency. It is necessary to develop approaches that allow converting these data into analytical indicators suitable for assessing the activities of enterprises in the context of sustainable development.

The relevance of these issues for Ukraine is growing as the processes of European integration become more active. Approaching the standards of the European Union is accompanied by increasing requirements for transparency of processes and indicators, in particular environmental and social aspects of management. Investors, insurers, and lenders are increasingly taking into account ESG indicators when assessing enterprises. Under such conditions, it is important to develop clear and analytically sound approaches to resource management.

The formation of the scientific basis for the implementation of sustainable development values in the agricultural sector has deep theoretical roots that precede the modern ESG paradigm. The scientific literature substantiates the need to manage business taking into account the interests of a wide range of stakeholders, which goes beyond exclusively financial goals [1]. This approach has formed the social and managerial basis for the further development of the concepts of responsible and sustainable business. The normative and value basis of sustainable development was formulated in the report of the World Commission on Environment and Development, where sustainable development is defined as a balance of economic, social and environmental needs of current and future generations [2]. Further development of this logic took place in the triple bottom line concept, which for the first time emphasized the need to evaluate the activities of enterprises according to three dimensions of performance [3]. It was this triune logic that was later transformed into the modern ESG structure. In the scientific literature of the mid-1990s, the approach to assessing the role of the environment in the development of enterprises changed noticeably. It was then that works appeared in which environmental requirements were considered somewhat differently than they had been done before. The authors drew attention to the fact that environmental regulations sometimes encourage enterprises to review production processes. As a result, companies begin to look for other technological solutions, reduce resource losses, or increase production efficiency. In this approach, environmental safety no longer looks only as an additional burden for business. It can become an impetus for changes that are subsequently reflected in the competitiveness of the enterprise [4]. At the beginning of the 2000s, this discussion received a different development. Gradually, attempts appeared to systematically reflect the environmental and social aspects of companies' activities in reporting. At this time, the practice of non-financial information disclosure was formed. One of the initiatives that played an important role in this process was the Global Reporting Initiative. Within this platform, indicators were proposed by which enterprises could describe their impact on the environment, resource use, and social aspects of work [5]. Later, such approaches began to be used as the basis for the formation of ESG indicator systems. Further development of this topic shifts attention to another aspect of the problem. Social and environmental issues are considered not separately from the economic activity of the enterprise, but in connection with the process of value creation. In this logic, sustainable development begins to be considered as one of the factors of long-term competitiveness of business [6]. In other words, sustainable development in their interpretation ceases to be only an external requirement for business. It becomes part of the enterprise strategy and can affect its long-term competitiveness [6]. Later, the attention of researchers began to shift to the question of how to measure the results of enterprise activities in such a coordinate system. Works appear that consider the role of information and analytical support for management. The importance of the correct selection of indicators used in the analysis of enterprise activities is emphasized [7].

The quality of management decisions also depends on the extent to which these indicators reflect real processes. It is precisely such approaches that have become the basis for the formation of more complex assessment systems that are used today in the field of ESG. This logic is developed in studies devoted to the modeling of risk management information systems and the use of monitoring data to assess complex technogenic and environmental processes [8, 9]. The direct agricultural ESG issues are revealed in works that analyze sustainable practices in agribusiness and national models of implementing ESG criteria. The works [10, 11] focus on the importance of ESG for agricultural development, while at the same time recording the limited operationalization of indicators and insufficient integration of digital analytics (DA). Similar conclusions are confirmed in other studies, where state regulation of investment activities in the agricultural sector is considered without the formation of a holistic ESG management system [12]. The current stage of research is characterized by a growing interest in the digital transformation of agribusiness as a factor of sustainable development. Digital technologies are considered as a catalyst for environmental and social performance, but the issue of transforming resource flows into measurable ESG indicators remains open [13]. This gap is also traced in studies devoted to climate adaptation of the agro-industrial sector and European integration challenges [14, 15]. Review works devoted to the interconnection of Industry 4.0, food systems and agroecosystems confirm the absence of unified models of resource data integration [16] and ESG metrics into an integrated management system [17, 18]. The regulatory dimension of this issue is systematically disclosed in the work. The authors of this publication have proven that in the agri-food sector, ESG is evolving from a voluntary corporate initiative to a mandatory regulatory standard. They concluded that the implementation of this standard requires digital provability, traceability of resource practices and the implementation of system analytics [19].

Thus, at this point in time, scientists have formed a multi-level theoretical and empirical foundation for the sustainable development of the agricultural sector. However, scientific developments remain somewhat fragmented in terms of combining ESG values, resource flow management and DA. It is this gap that determines the need to develop integrated digital-analytical mechanisms for ESG-oriented resource management as the basis for implementing sustainable development values in the agricultural sector.

Thus, *the object of research* is the process of forming an ESG management system based on digital analytics (DA). The work of enterprises in the agricultural sector is associated with the constant use of various types of resources – primarily land, water, energy, materials and labor. The way in which these resources are involved in production has a significant impact on both the economic results of management and the state of the environment. At the same time, this affects the development of rural areas and the living conditions of the population living there.

The aim of research is to form an ESG management system based on digital analytics. To achieve this aim, a number of interrelated tasks are planned. Among them:

1) analyze scientific approaches to ESG resource management in the agricultural sector;

2) identify the possibilities of using digital tools to formalize data in the form of ESG indicators;

3) develop a mechanism for integrating resource data and ESG indicators into the management system of an agricultural enterprise;

4) form models for assessing the relationship between the efficiency of resource use and the effectiveness of ESG indicators.

2. Materials and Methods

The subject of research is the relationship between resource use in agriculture and the performance of agricultural enterprises, assessed using ESG approaches. It examines how information on the use of natural resources can be used to assess the environmental, social and management characteristics of agricultural enterprises. In this context, digital analytics tools play a significant role, as they allow for the collection and processing of large volumes of production data.

The main hypothesis of research is that combining ESG principles with the capabilities of digital analytical tools can contribute to a more rational use of resources in agriculture. When information about production processes becomes systematic and accessible for analysis, enterprises gain more opportunities to evaluate their own activities and adjust management decisions. This, in turn, can affect the level of resource efficiency of production, the environmental characteristics of enterprises and the long-term sustainability of their development.

ISSN-L 2664-9969; E-ISSN 2706-5448

Description of variables: The research used various indicators, which can be conditionally divided into several groups. Firstly, this concerns the use of resources: how much land is cultivated, how much water and energy is consumed, what amounts of fertilizers are used. Secondly, these are the results of activities – production volumes, income, productivity. Indicators that characterize the environmental component were taken into account separately, for example, the level of resource intensity or other generalized ESG assessments. Taken together, this ensured the comprehensiveness of the research.

Data sources: Data for analysis were taken from open sources. These are state statistics, materials from international organizations, and reports from agri-food companies themselves. Some information had to be collected from different sources and brought together, since it is not always presented in the same format. But as a result, it was managed to form a sufficient base to trace general trends.

Processing algorithms: As for data processing, first the data was brought to a normal form – gaps were removed, indicators were aligned so that they could be compared with each other. Then the values had to be recalculated, for example, per hectare or unit of production. Later, an analysis of the relationships between the indicators was performed – how one changes relative to the other. And on this basis, a model was built that allows to assess how resource use is related to the results of activities according to the ESG approach.

3. Results and Discussion

3.1. Analysis of scientific approaches to ESG resource management in the agricultural sector

A review of scientific works devoted to ESG and resource management in the agricultural sector shows a rather motley picture. Researchers work in different directions, which only partially overlap. Because of this, a common methodological basis is still lacking. On the one hand, this situation gives rise to many different analytical approaches. On the other hand, it complicates the practical application of sustainable development ideas in the activities of agricultural enterprises. Table 1 summarizes the main directions, their content and limitations that are most often mentioned in scientific works. This makes it possible to see how the scientific discussion develops and why certain discrepancies arise between individual approaches.

One of the dominant trajectories is associated with the ESG indicator logic, within which the management of agricultural enterprise resources is interpreted through a system of environmental, social and management indicators. The methodological basis of this approach is formed in works devoted to the selection, structuring and aggregation of indicators for the assessment of complex socio-economic processes [1]. It is also based on the concept of sustainable development and three-component business performance [2, 4, 5]. The advantage of this approach is the possibility of forming comparable assessments and including agricultural enterprises in the global ESG discourse. Despite this, the static interpretation of resources limits the reflection of their dynamic role in the formation of ESG performance.

Another trajectory is based on a risk-oriented approach, in which ESG is used as a tool for identifying and minimizing environmental and production risks [8, 9]. For the agricultural sector, this creates a methodological basis for increasing the sustainability of production, but reduces resources mainly to risk factors, rather than to strategic development assets. In scientific publications in recent years, there has been a noticeable increase in interest in the use of information systems and digital technologies in the field of resource management of agricultural enterprises. In such works, resources are often considered not only as the material basis of production, but also as data flows that can be used in management decision support systems [7, 9, 13, 16]. It is in this environment that the basis for the development of digital analytics is gradually being formed. However, in most studies, the environmental, social and management aspects of enterprise activities are considered separately from the analysis of resource flows. In view of this, the connection between digital data and ESG indicators remains insufficiently expressed.

Materials summarized in Table 1 also show another important trend. In many countries, ESG is no longer just a voluntary practice and is gradually moving into the sphere of regulatory requirements for agri-food chains [19]. At the same time, studies from different regions draw attention to similar difficulties. These are often cited as data fragmentation, uneven development of digital infrastructure, and limited opportunities to use information when making management decisions [20, 21]. As an analysis of scientific sources shows, these areas of research are developing mostly in parallel. Some works focus on a system of indicators, others on risk assessment, and some on digital technologies or regulatory requirements.

Table 1

Directions for the development of scientific approaches to ESG resource management in the agricultural sector

Areas	Key analytical focuses	Methodological advantages	Key limitations for practical implementation of ESG
ESG indicatorization	Formation and aggregation of ESG indicators	Comparability, integration into the global ESG discourse	Staticity of assessment, ignoring the dynamics of resource flows
Risk-oriented ESG management	Identification of environmental and production risks	Increasing resilience, adapting to the risk situation	Limited treatment of resources as a strategic asset
Information and analytical systems for resource management	Digital decision support systems	CA basis, improving data quality	ESG is not a system-forming element
Institutional and regulatory support for ESG	Investment policy, sustainability at the macro level	Forming the ESG regulatory context	Gap between macro- and micro-levels of management
Digital transformation of agribusiness	Digital technologies as a driver of efficiency	Potential for reducing resource intensity	Lack of rules for transforming data into ESG
Industry 4.0 integration with agribusiness and food systems	Technological solutions and sustainable systems	Interdisciplinarity	Lack of a holistic ESG analytical framework
National and regional models of ESG implementation	Local features of ESG implementation	Contextualization of ESG	Supporting DA role
Regulatory evolution of ESG in the context of CSRD	ESG as a mandatory management requirement	Increasing measurability and accountability	Risk of ESG formalization
ESG in agribusiness systems of developing countries	Data and infrastructure limitations	Identifying structural barriers	Data fragmentation, weak ESG integration

Note: developed on the basis of [1, 2, 4–16, 19–21]

Because of this, there is still a lack of a coherent approach that would combine data on resource use with ESG indicators and allow them to be applied in management practice. It is this disunity of approaches that explains why in many cases large data sets do not turn into understandable indicators of sustainable development.

3.2. Exploring the possibilities of using digital tools to formalize data in the form of ESG indicators

In modern agricultural production, digital analytics is gradually beginning to play the role of a kind of "bridge" between everyday production data and indicators used to assess the sustainable development of the enterprise. This is a situation where information on the use of water, energy, fertilizers, seeds or plant protection products is collected directly during the production process. Such information can come from various sources: field sensors, satellite observations, electronic production logs, accounting systems or traceability platforms. The collected data usually needs to be organized, as they come in different formats and with different accuracy. After they are coordinated according to directories, quality rules and geographical reference, it becomes possible to perform further analytical analysis.

It is at this stage that digital analytics begins to play an important role. It allows for the regular calculation of indicators related to the environmental, social and governance aspects of the enterprise's activities and their comparison over time. This is important, in particular, when there is a need to confirm the origin of products or to prove that production complies with modern traceability requirements in agri-food chains [22, 23].

It is also important that digital tools help to connect information from the level of an individual farm with broader sustainability indicators used by investors, partners or regulators. For example, geographically linked data on fields or batches of products can serve as an evidentiary basis when verifying the origin of raw materials. These data can also be used to verify compliance with requirements for preventing deforestation in production chains [19, 23]. Without such confirmations, modern agricultural enterprises find it increasingly difficult to integrate into international markets and value chains.

As a result, digital analytics effectively helps to "translate" production information into the language of sustainability indicators. This enables data on resource use to be transformed into understandable indicators that are used in the process of enterprise management. An example of such transformation of resource data into measurable ESG indicators is given in Table 2.

Table 2

Transformation of resource flows into ESG indicators

Information type	Sources	ESG indicators
Fertilizer application rates	Telematics of machinery, differential application maps	Nitrogen intensity, kg/ha
Water usage data	Water meters, irrigation sensors	Water intensity of production, m^3/t
Energy consumption	Fuel accounting, ERP systems	Greenhouse gas emissions scope 1–2, t CO_{2e}
Crop yield	Combine sensors, laboratory analyses	Land productivity, t/ha

Note: developed on the basis of [7, 9, 12, 13, 16, 19, 22, 23]

Comparing the information provided in Table 2 with estimates of the scale of the climate impact of agri-food systems allows to understand why much attention is paid to working with data in agricultural production. According to FAO estimates, in 2022, total emissions of agri-food systems amounted to approximately 16.2 billion tons of CO_{2e}. Over the past few years, this indicator has hardly changed, which indicates the difficulty of reducing it without more precise control of production processes [22]. In such conditions, there is a need to work with more detailed data on resource use at the level of individual technological operations.

When an enterprise does not have a well-established digital data system, it usually uses generalized or average values of indicators. Such estimates give only an approximate idea of the situation and almost do not show where the greatest resource costs arise. For example, within a single farm, different fields or crops may differ significantly in terms of water, fertilizer or energy consumption. If these differences are not recorded, it is difficult to identify real cost overruns and, accordingly, it is difficult to justify investment or environmental decisions.

Corporate examples from recent years provide some insight into how digital tools are used in practice. Olam's 2021 reports describe the use of the AtSource platform and mobile tools for interacting with farmers. Thanks to such systems, information on the social and environmental aspects of production is gradually translated into quantitative indicators.

In particular, the coverage of data supply chains, production areas and the number of farmers connected to digital platforms in 2020–2021 are recorded [24]. The importance of such systems lies in the fact that the accumulated data forms the basis for risk assessments – for example, the risk of deforestation, violations of environmental practices, etc.

Another example can be found in the Cargill Impact Report 2024. It states that the assessment of the company's climate performance became possible after combining data on energy consumption, fuel use and other parameters in a single system. This made it possible to track the change in absolute operational emissions compared to the 2017 baseline [25]. For the agricultural sector, this experience shows that climate performance begins to become manageable only when there is a consistent data chain – from primary measurements to final ESG indicators.

Another area of use of digital technologies is related to more precise control of resource use directly in the field. The Bayer Sustainability Report 2022 emphasizes the role of digital agriculture, which allows collecting large amounts of agronomic information from machinery, sensors and other sources. Such data is used to optimize the application of fertilizers, plant protection products and water, as well as to improve production efficiency. One tool used for this is the Climate FieldView platform [26]. Thanks to such technologies, it becomes possible to more accurately assess indicators related to water or nitrogen intensity of production and other environmental parameters.

The growing interest in digital solutions is also confirmed by international financial institutions. According to the World Bank, as of 2021, 53 investment projects with a total value of about 1.15 billion USD were implemented in the field of digital agriculture [27]. This indicates a gradual transition from individual experimental initiatives to the wider implementation of digital systems in the agricultural sector.

Taken together, the examples given show that digital analytics is increasingly being seen as a tool that combines increasing production productivity with achieving sustainable development goals. A summary of corporate examples of the use of such approaches in 2020–2024 is presented in Table 3. Based on these, it is possible to see how digital platforms, geographic data and analytical tools are gradually shaping the ESG assessment system at the enterprise and supply chain levels [24–26].

Table 3

Corporate DA examples as a mechanism for forming ESG indicators for the period 2020–2024

Companies	The years when companies began to actively use digital tools	Types of information accumulated in digital systems	ESG indicators
Olam	2020–2021	The AtSource platform accumulates information about farmers, farms and product delivery routes	Share of supplies to a specific manufacturer
	2022–2024	The system adds coordinates of land plots, information about crops and growing regions	Level of deforestation risks in supply chains
Cargill	2020–2022	Enterprises are gradually moving to digital accounting of energy and fuel used in production	Volume of greenhouse gas emissions (scope 1–2), t CO_{2e}
	2023–2024	Data on energy consumption and production are combined in a single climate analytics system	Change in emissions level
Bayer	2022–2024	The FieldView digital platform collects agronomic data: yield, resource use, growing conditions	Level of efficiency in the use of water, energy and other resources

Note: developed on the basis of [24–26]

The information presented in Table 3 allows to see a certain change in approaches to working with data in agri-food companies. If previously digital tools were used mainly for individual control elements, now they are increasingly becoming the basis for broader management of sustainability indicators. This is a transition from simple observation of individual indicators to a more systematic analysis of resource flows in production. The experience of Olam company well illustrates this evolution. In the initial stages, digital platforms were used mainly to record the number of farmers and areas covered by sustainable supply programs. Over time, the accumulated data began to perform a different function – they became an evidentiary base for confirming the compliance of supply chains with the requirements of responsible production [24]. A similar logic can be traced in other examples.

The materials of Cargill show that it became possible to assess the real climate indicators of the company only after a long accumulation and coordination of data on energy and fuel use across different divisions [25]. In turn, Bayer's experience demonstrates that precision farming technologies help to link daily agronomic operations with environmental indicators used in the ESG system [26]. A separate aspect of this topic is reflected in Table 4. It shows how, at the European Union level, digital tools are gradually moving from the category of experimental solutions to the sphere of mandatory requirements. This primarily concerns product traceability systems and the use of geolocation data, which are increasingly seen as a necessary element of managing the sustainable development of agri-food supply chains [22, 23].

Table 4

Regulatory examples of ESG DA in EU agricultural supply chains for the period 2020–2024

Years	Digital tools	Data types	Management implications for ESG
2020	Implementation of pilot data traceability systems	Practice location-based geodata collection of supply chains	Initiating the process of forming digital databases
2021	Digital maps of business and environmental risks	Formation of geolocation databases	Forming regulatory control algorithms
2022	Implementation of EUDR analytics	Establishment of requirements for land coordinates	Standardizing the evidentiary value of digital data
2023	Adoption of EU implementing acts	Legislative implementation of mandatory geolocation traceability	Legislative implementation of mandatory digitalization of ESG management
2024	Implementation of EUDR compliance monitoring	Introduction of regular mandatory verification of deforestation-free supply chains	Practice of compliance and regulatory risk management

Note: developed on the basis of [22, 23]

Regulatory changes are gradually changing the role of digital tools in the ESG field. What was used mainly on the initiative of companies themselves a few years ago is now increasingly becoming a requirement of rules and standards. Companies are forced not only to declare environmental or social results, but also to confirm them with verifiable data.

A good example of this is the introduction of requirements for geographical traceability of products within the framework of the EUDR regulation. Information about field coordinates, the origin of raw materials or product movement routes is actually part of the daily work of agricultural enterprises. Such data is used during inspections, audits and reporting, so they become part of normal management procedures [22, 23].

If to look at the results summarized in Table 3 and Table 4, another trend is noticeable. During 2020–2024, digital systems are increasingly used to work with data on resources, production operations and supply chains. This is precisely why it is possible to translate such data into understandable indicators of sustainable development. As a result, practices that are formed within companies and the requirements of regulators are gradually converging, creating a common basis for managing ESG indicators in agricultural business.

3.3. Development of a mechanism for integrating resource data and ESG indicators into the management system of an agricultural enterprise

In the activities of agricultural enterprises, information on resources and the assessment of sustainable development have long been used separately. Data on land, water, energy consumption or material costs were collected primarily for production needs: planning field work, accounting for costs or calculating the cost of production. ESG indicators appeared much later and were most often used when preparing reporting or analytical materials. Due to this practice, production processes and the assessment of their environmental and social impacts were actually not connected.

Over time, other approaches began to appear in research and practice. The focus became on how to use existing production data to manage the enterprise. That is, information that had previously simply accumulated in journals or databases began to be considered as a source for analysis. First, the data is collected, then it is brought to a common structure, checked, and only then the results of the farm's work are assessed on their basis. After that, conclusions can be drawn about technologies, resource use, or production organization. The starting point in such work is the resources themselves with which the enterprise works. This includes information on land plots, water consumption, energy use, materials, and labor costs. Such data appears from various sources: field journals, technical systems, agronomic services, or financial documents. Because of this, they often have different formats and are not always easily combined with each other. Therefore, when working with such information, there is usually a need to organize it. The data are brought to a common form: time periods are aligned, types of operations are specified, and units of measurement are recorded in the same way. After such ordering, it is already possible to work with them analytically and use them in further calculations.

It has been repeatedly noted in the literature that the incompatibility of different data sets is one of the reasons for the limited practical value of some ESG indicators in the agricultural sector [7, 12].

When information is brought to a common structure, it becomes possible to analyze it more deeply. In this case, it is important to understand how the use of resources affects production results. For example, to assess the water or carbon intensity of products, information on irrigation, energy consumption, crop yields and other parameters of the production process is combined. This approach allows to see not only general indicators, but also the relationships between technological operations and their environmental consequences [13, 22, 26].

The results obtained can be arranged according to the ESG structure. In this case, each indicator has a clear source of origin and is associated with specific production processes. It is this binding that makes the indicators more understandable both for internal management of the enterprise and for external audits. In the practice of large agri-food companies, a similar system allows to confirm the reliability of environmental and social performance during audits or reporting [24, 25].

After that, the indicators can be used in the management process. In this case, they no longer perform only a reporting function. Information on resource use and relevant ESG indicators can influence the choice of technologies, crop structure, equipment investments or approaches to cooperation with suppliers. An additional incentive for such integration is created by new requirements for transparency of production and traceability of supply chains. That is why in modern agribusiness more and more attention is paid to combining resource data with a system of sustainable development indicators. A generalized mechanism of such an approach is presented in Table 5.

The described mechanism shows that the combination of resource data with ESG indicators is much broader than just a technical combination of different information systems. In fact, if to talk about a different organization of the management process. Resource data becomes the starting point for analysis, on the basis of which the corresponding indicators are formed, after which they are used in decision-making. With this approach, each indicator has a clear origin and is directly related to specific production processes.

During 2020–2024, a similar practice began to gradually spread in the agricultural business. For many enterprises, it became one of the ways to strengthen their positions in the market, attract financing and confirm compliance with the requirements of sustainable development. In such conditions, ESG indicators are increasingly used not only in reporting, but also in the daily management of the enterprise.

Table 5

Mechanism of integration of resource data and ESG indicators into an integrated agribusiness management system

Integration stages	Characteristics of the stages	Data examples	Why is it needed in management
Recording resource usage	At the initial stage, the enterprise simply collects information on how many resources are actually consumed in production operations. The data can come from field logs, technical systems or accounting	Water, m^3; diesel fuel, l; fertilizers, kg; crop area, ha	Initial information is formed, without which further analysis is impossible
Reconciling and organizing information	Since the data comes from different sources, they have to be brought into the same form. Enterprises create their own directories of fields, crops, operations, sometimes adjusting units of measurement or time periods	Field database, crop list, technological operations calendar	Data becomes suitable for comparison between different areas and seasons
Analytical work with indicators	At this stage, the collected information is already used for calculations. Most often, they determine how many resources are consumed per unit of output or area	Water intensity of production, m^3/t; energy intensity of production; fertilizer consumption per hectare	It is possible to see where resources are used less efficiently
Transition to ESG indicators	Some of the production data begin to be linked to environmental or social indicators that are used in non-financial reporting	CO_{2e} emissions; share of traceable products, %; occupational safety indicators	The company receives a set of indicators that meet ESG requirements
Use in decision-making	After that, the indicators begin to be used not only in reporting, but also in daily management. For example, when planning investments or changing production technology	Results of analysis of water, energy or material consumption	There is an opportunity to increase work efficiency and reduce resource load

Note: developed on the basis of [7, 12, 13, 16, 19, 23–25]

3.4. Formation of a model for assessing the relationship between resource efficiency and ESG performance

In the agricultural sector of Ukraine, the issue of sustainable resource use has begun to be discussed much more actively only in recent years. Previously, for most enterprises, this was not a key management topic. The main attention was paid to yield, production costs and the ability to sell products on foreign markets. The situation gradually changed after the agricultural industry faced new economic conditions and at the same time the requirements of international markets increased.

For Ukrainian agriculture, this issue has a practical dimension. A significant part of agri-food products is exported to the countries of the European Union, so the rules for accessing this market directly affect the activities of enterprises. European buyers and regulators are increasingly paying attention to where the products come from, under what conditions they were produced and whether environmental and social requirements were met. In such conditions, it is no longer enough for enterprises to simply ensure the necessary volumes of supplies or a competitive price.

ISSN-L 2664-9969; E-ISSN 2706-5448

An important factor has also been the new rules that are gradually being introduced in the European Union. They concern the disclosure of non-financial information and the traceability of agri-food chains. These include the requirements enshrined in the CSRD and EUDR, which provide for more detailed confirmation of the origin of products and the conditions of their production. As a result, the issue of resource use and compliance with sustainable development standards is becoming increasingly important for Ukrainian agricultural enterprises.

As a result, the ability of an enterprise to show how land resources are used is becoming increasingly important as a condition for access to the EU market. In addition, emissions and how social standards are observed in production are monitored.

The situation is further complicated by the fact that agri-food systems in the world remain a significant source of greenhouse gas emissions. According to FAO estimates, in 2022 they amounted to approximately 16.2 billion tons of CO_{2e} [22]. At the same time, researchers note that a significant part of the potential emission reduction is associated with changes in the use of land resources, energy and agricultural technologies. For Ukraine, where the area of agricultural land exceeds 32 million hectares, these issues are of not only environmental but also economic importance.

In view of this, the transition to ESG-oriented resource management can be considered as one of the directions of long-term development of the agricultural sector. This approach allows combining the restoration of production with the requirements of environmental and climate policy, which are gradually being formed in the European economic space. The main directions of such transformation for agricultural enterprises in Ukraine are summarized in Table 6.

Table 6

Directions for implementing ESG-oriented resource management in the agricultural sector of Ukraine

Areas	Nature of changes	Expected result	Related European requirements
Harmonization of reporting	Adaptation of resource accounting to non-financial reporting standards	Increased transparency of resource use	CSRD
Land use traceability	Identification of fields and product batches by coordinates	Confirmation of product origin	EUDR
Resource efficiency analysis	Calculation of water, energy and fertilizer intensity	Reduced environmental impact	ESRS E1–E5
Social indicators	Accounting for working conditions and safety	Increased social responsibility	ESRS S1–S4
ESG integration into management	Using ESG metrics in decision-making	Long-term sustainability of enterprises	EU funding programs

Note: developed on the basis of [19, 22, 23, 27]

For Ukraine, one of the first steps in this direction is to create clear institutional conditions for resource management taking into account ESG principles. Currently, accounting for land, water, energy or other resources is in most cases associated primarily with the financial reporting of enterprises. Such data is rarely used to assess the environmental or social consequences of economic activity. As a result, information on resources and sustainable development indicators often exist separately. The transition to the standards used in EU countries requires not just copying regulatory documents, but changing approaches to data accounting. This involves their gradual transition to a digital format, which makes it possible to compare information and make it understandable for different market participants.

Another important direction is the transparency of the use of land resources and the movement of products in supply chains. In the new European rules, confirmation of the origin of products, in particular the absence of deforestation plays a significant role. Because of this, information about the geographical location of land plots and the history of their use is becoming more important than ever. Accurate recording of information about land and production is becoming increasingly important for agricultural enterprises. Previously, field accounting was often limited to internal farm documents or general maps. Now the situation is changing. In many cases, there is a need to have electronic maps of fields indicating coordinates, history of their use and connection with product batches. Such information is needed not only by the enterprise itself. It is also used when confirming the origin of products on external markets. According to the European Commission, the lack of clearly confirmed geographical data often makes it difficult for suppliers from third countries to enter the EU markets [23]. At the same time, many farms still have significant reserves for more economical use of resources. This applies to water, energy, fertilizers or other materials used in production. The reason is that modern digital tools and technologies for precision agriculture are not evenly distributed. In cases where they are used, it is possible to better plan technological operations and input rates. World Bank research shows that such solutions can reduce the resource intensity of production by approximately 10–20% [27].

The social aspects of agricultural enterprises are more difficult to assess. In many regions, employment is seasonal, and some workers are hired temporarily. Because of this, information on working conditions or employment is not always easy to systematize. However, tools are gradually emerging that help organize this data. In practice, enterprises use various methods of recording information about employees. Some still keep paper logs of briefings or work time records. Other farms already use simple spreadsheets or separate programs for working with personnel. Sometimes such records are made only during inspections. Sometimes – constantly. As a result, a more orderly picture of how people's work is organized on the farm is gradually forming.

Noticeable changes are also taking place in the attitude towards sustainable development indicators. A few years ago, they were of interest mainly to researchers or report writers. Now the situation is different. When an agricultural enterprise approaches a bank or potential investor, the conversation often goes beyond financial results. They also ask about other things: how resources are used, what environmental impacts production has, what conditions people work in. Sometimes, it is this information that becomes crucial for making financial decisions.

In general, the approach to sustainable development in the agricultural sector is gradually changing. Previously, environmental and social issues existed as if separately from the daily work of the enterprise. They could be mentioned in reports or in separate programs. Now there is an increasing need to link these topics with real production processes. It is difficult to do this without data. That is why enterprises are beginning to pay more attention to how information about land, resources, people and business results is collected.

In the previous research results, DA was substantiated as a key mechanism for transforming resource flows into manageable ESG indicators. In turn, ESG performance as a dynamic result of the interaction of resource efficiency, digital maturity and contextual conditions of the functioning of agricultural enterprises. These provisions serve as a methodological basis for further formalization of the relationships between resource flows, DA and ESG performance in the form of an economic and mathematical model. Such formalization is aimed at quantitatively reproducing the dynamics of resource management in agricultural enterprises. This allows to move from the conceptual justification of the DA role to the analytical verification of its impact on ESG indicators.

In this context, the model is built on the basis of primary resource data recorded in digital systems and describes the mechanism for their transformation into derived indicators of efficiency and effectiveness. In this case, derived indicators of efficiency reflect the degree of rational use of resource flows in the production process. They characterize the relationship between the volumes of resources involved and the resulting volume of production. In turn, derived indicators record the managerial consequences of resource behavior in the form of achieved ESG parameters. These indicators reflect the environmental, social and managerial results of activities in time dynamics. Within the framework of the model, indicators of efficiency and effectiveness are considered as derivatives, since they are formed by analytical transformation of primary resource data recorded in digital systems. These are systems such as: ERP, WMS, precision agriculture systems, geoinformation monitoring platforms.

Let i denote an agricultural enterprise or production unit, t – observation period. Primary resource flows recorded in digital systems are given by the vector

$$R_{i,t} = \{Li,t;\ Wi,t;\ Ei,t;\ Mi,t;\ Hi,t\}, \quad (1)$$

where Li,t – land use, ha; Wi,t – water use, m^3; Ei,t – energy consumption, kWh; Mi,t – material resources, kg; Hi,t – labor costs, man-hours.

Based on the DA, the following resource intensity indicators were formed:

$$li,t = Li,t/Qi,t; \quad (2)$$

$$wi,t = Wi,t/Qi,t; \quad (3)$$

$$ei,t = Ei,t/Qi,t; \quad (4)$$

$$mi,t = Mi,t/Qi,t; \quad (5)$$

$$hi,t = Hi,t/Qi,t, \quad (6)$$

where $Q_{i,t}$ – production volume, tons.

To reduce the impact of anomalous values and heterogeneity of data sources, normalization is performed using a modified min-max procedure with preliminary clipping of extreme values along open industry boundaries:

In order for the resource intensity indicators to be comparable with each other, they are first brought to a single scale. For this, a standard normalization procedure is used

$$zi,t = (xi,t - x^*min)/(x^*max - x^*min). \quad (7)$$

In this notation, xi,t denotes the value of a certain resource intensity indicator. In the calculations, it may correspond to one of the following indicators: li,t; wi,t; ei,t; mi,t; hi,t. The limits x^*min and x^*max define the interval within which the indicator in the studied population changes. They are determined based on the actual distribution of values in the sample.

After normalizing individual variables, it is possible to proceed to generalizing the results. For this purpose, an integral indicator of resource efficiency is introduced

$$REi,t = 1 - (\alpha L,t{\cdot}zli,t + \alpha W,t{\cdot}zwi,t + \alpha E,t{\cdot}zei,t + \alpha M,t{\cdot}zmi,t + \alpha H,t{\cdot}zhi,t), \quad (8)$$

where $\alpha L,t,\ \alpha W,t,\ \alpha E,t,\ \alpha M,t$ ma $\alpha H,t$ reflect the relative weight of the corresponding components. The values of these coefficients are obtained from a combination of two sources of information. One of them is related to the regulatory guidelines of environmental and social policy. The other is related to the statistical characteristics of the indicators themselves in the studied population. All weights are normalized so that their sum equals one.

The quality of digital data used in the calculations is separately taken into account. For this purpose, the index

$$DQi,t = \omega_1{\cdot}Compi,t + \omega_2{\cdot}Regi,t + \omega_3{\cdot}Grani,t. \quad (9)$$

The component $Compi,t$ reflects what share of resource flows the enterprise covers with digital data. The indicator $Regi,t$ characterizes the regularity of obtaining measurements. The variable $Grani,t$ describes the degree of detail of information - how accurately it is tied to specific operations or production areas. The values of the weights ω are determined based on the results of statistical data analysis, after which they are normalized to ensure comparability of the results.

The context block $X_{i,t}$ in the model is interpreted as a system of control variables. This block covers natural characteristics formed on the basis of open geospatial and statistical data. It also ensures the correct separation of the effects of resource management and DA from the influence of objective natural and territorial conditions of agricultural production.

ESG performance is presented in the form of three interrelated components: environmental ($E_{i,t}(S)$), social ($S_{i,t}(S)$) and management ($G_{i,t}(S)$), integrated into the indicator

$$ESGi,t = \beta E \cdot Ei,t(S) + \beta S \cdot Si,t(S) + \beta G \cdot Gi,t(S), \quad (10)$$

where $\beta E,\ \beta S,\ \beta G$ – weights that can vary depending on the regulatory and industry context. In sum, they amount to 1.

Taking into account the limited sample, the model is implemented modularly. That is, it is built as a set of relatively autonomous analytical blocks, each of which is evaluated separately and is responsible for its own logic of the relationship between variables. In practice, this means that the environmental, social and governance components of ESG are described by independent equations with the same structure, but with different parameters. This approach reduces the requirements for the sample size, reduces the risk of unstable estimates and allows for a gradual complication of the model by adding new components or effects. The basic specification without threshold effects has the form:

1) ecological component

$$Ei,t(S) = \rho E \cdot Ei,t{-}1(S) + \theta E \cdot \ln(REi,t{-}1) + \varkappa E \cdot DQi,t{-}1 +$$
$$+ \lambda E \cdot Xi,t + uE,i + \tau E,t + \varepsilon E,i,t; \quad (11)$$

2) social component

$$S_{i,t}(S) = \rho S \cdot S_{i,t-1}(S) + \theta S \cdot \ln(RE_{i,t-1}) + \varkappa S \cdot DQ_{i,t-1} +$$
$$+ \lambda S \cdot X_{i,t} + uS,i + \tau S,t + \varepsilon S,i,t; \quad (12)$$

3) management component

$$G_{i,t}(S) = \rho G \cdot G_{i,t-1}(S) + \theta G \cdot \ln(REi,t{-}1) + \varkappa G \cdot DQ_{i,t-1} +$$
$$+ \lambda G \cdot X_{i,t} + uG,i + \tau G,t + \varepsilon G,i,t. \quad (13)$$

Using lag values $RE_{i,t-1}$ and $DQ_{i,t-1}$ reduces the risk of endogeneity and strengthens the causal interpretation of the results. Individual fixed effects $uE,i,\ uS,i,\ uG,i$ reflect constant characteristics of enterprises. In turn, $\tau E,t,\ \tau S,t,\ \tau G,t$ are common to the entire set of changes in operating conditions in period t. ε are random disturbances with zero mathematical expectation.

The extended specification of the model is applied at the stage when the temporal and spatial volume of data is sufficient to identify more complex dependencies between resource efficiency, DA and ESG performance. Its analytical idea is to test the hypothesis that the impact of resource efficiency on ESG is not autonomous, but is systematically modified by the level of digital data quality. To do this, a cross term $ln(REi,t–1) \cdot DQi,t–1$ is introduced into the relevant equations. It allows to formalize the mechanism of complementarity between resource management and CA. The impact of resource efficiency on ESG performance increases with increasing digital data quality. Resource management and DA act mutually reinforcingly, and their combined effect is greater than the sum of their individual effects. In general, the extended equation for the k–th ESG component can be represented as

$$ESG_{i,t}{}^{k} = \rho_k \cdot ESG_{i,t-1}{}^{k} + \theta_k \cdot ln(RE_{i,t-1}) + \varkappa_k \cdot DQ_{i,t-1} +$$

$$+ \mu_k \cdot (ln(REi,t-1) \cdot DQi,t-1) + \lambda_k \cdot Xi,t + uk,i + \tau k,t + \varepsilon k,i,t, \quad (14)$$

where the parameter μk reflects the marginal increase in the impact of resource efficiency on *ESG* performance under the condition of increasing the quality of digital data. Additionally, a threshold indicator variable $I(DQi,t - 1 \geq DQ^*)$ is introduced, which is equal to 1 if the critical level of digital quality DQ^* is reached and 0 otherwise. This allows to evaluate the model in the form of a regime specification. The parameters θk and μk can take on different values below and above the digital threshold. This analytically reflects the transition from declarative to operational use of *ESG* indicators in the agricultural enterprise management system.

The stability check of the obtained estimates within the model is formalized as a system of alternative specifications and scenarios for which the same structural parameters are estimated and their behavior is compared. The basic object of analysis is the vector of key parameters

$$\Theta^k = \{\theta^k, \varkappa^k, \mu^k\}, \quad (15)$$

where θ^k reflects the impact of resource efficiency; $\varkappa^k$ – the direct impact of digital data quality; μ^k – the DA amplification effect for the k-th ESG component.

The first block of the robustness test is based on the variation of the weights in the integral indices. Let $\alpha(s) = \{\alpha L(s), \alpha W(s), \alpha E(s), \alpha M(s), \alpha H(s)\}$ – s-th weighting scheme for the resource efficiency index, and a $\omega(r) = \{\omega_1(r), \omega_2(r), \omega_3(r)\}$ – r-th weighting scheme for the digital data quality index. For each combination (s, r), alternative indices are formed:

$$RE_{i,t}(s) = 1 - \Sigma_j \alpha_j(s) z_{ji,t}; \quad (16)$$

$$DQ_{i,t}(r) = \Sigma_m \omega_m(r) D_{m,i,t}, \quad (17)$$

where $D_{m,i,t}$ – m-th component of the digital data quality index. $D_{m,i,t}$ corresponds to the components $Comp_{i,t}$, $Reg_{i,t}$, $Gran_{i,t}$.

After that, the model is estimated

$$ESG_{i,t}{}^{k} = \rho k \cdot ESG_{i,t-1}{}^{k} + \theta_k(s,r) \cdot ln(RE_{i,t-1}(s)) + \varkappa_k(s,r) \cdot DQ_{i,t-1}(r) +$$

$$+ \mu_k(s,r) \cdot (ln(RE_{i,t-1}(s)) \cdot DQ_{i,t-1}(r)) + \lambda_k \cdot X_{i,t} + u_{k,i} + \tau_{k,t} + \varepsilon_{k,i,t}. \quad (18)$$

The stability of the parameters is determined by the following conditions:

$$sign(\theta^k(s,r)) = const, |\theta^k(s,r) - \theta^k(0,0)| \leq \delta_\theta; \quad (19)$$

$$sign(\varkappa^k(s,r)) = const, |\varkappa^k(s,r) - \varkappa^k(0,0)| \leq \delta_\varkappa; \quad (20)$$

$$sign(\mu^k(s,r)) = const, |\mu^k(s,r) - \mu^k(0,0)| \leq \delta_\mu, \quad (21)$$

where $(0,0)$ corresponds to the basic weighting scheme. This means that the configuration of the weighting coefficients of the integral indices is initially given, which is used as a standard for comparing the results under alternative weighting options and checking the stability of the estimates; δ_θ, $\delta_\varkappa$, δ_μ – permissible deviation limits of the parameters. δ_θ, $\delta_\varkappa$, δ_μ, ε – pre-specified permissible thresholds.

The second block of stability checking concerns alternative procedures for normalizing resource indicators. Let $N_p(\cdot)$ denote the p-th normalization procedure, for example, min-max, quantile or z-standardization. Then

$$z_{ji,t}(p) = Np(x_{ji,t}); RE_{i,t}(p) = 1 - \Sigma_j \alpha_j zj_{i,t}(p). \quad (22)$$

For each p, the model is estimated and a vector of parameters $\Theta^k(p)$ is formed. Stability is confirmed if the stability of the estimated parameters is checked by comparing their sign and magnitude with the base version of the model. For this purpose, the condition

$$sign(\Theta_k(p)) = sign(\Theta_k(0)), \text{ and } ||\Theta_k(p) - \Theta_k(0)|| < \varepsilon, \quad (23)$$

where the symbol $||\bullet||$ is used to denote the Euclidean norm, and ε sets the limit level of permissible deviation. If the difference between the estimates does not exceed this threshold, the parameter is considered stable.

It is separately analyzed how the results change with different compositions of explanatory variables. Let $Xi,t(q)$ denote the q-th configuration of the context vector. It is formed by adding or removing variables describing climatic conditions, soil properties, or production characteristics. For each such configuration, the model is estimated:

$$ESGi,tk(q) = \rho k \cdot ESGi,t_{-1}k + \theta k(q) \cdot ln(REi,t_{-1}) + \varkappa k(q) \cdot DQi,t_{-1}, \quad (24)$$

$$\mu k(q) \cdot (ln(REi,t_{-1}) \cdot DQi,t_{-1}) + \lambda k(q) \cdot Xi,t(q) + uk,i + \tau k,t + \varepsilon k,i,t. \quad (25)$$

After that, the results are compared with the base specification. It is checked whether the direction of influence of the key variables is preserved. Formally, this can be written as

$$sign(\theta k(q)) = sign(\theta k(0));$$

$$sign(\varkappa k(q)) = sign(\varkappa k(0));$$

$$sign(\mu k(q)) = sign(\mu k(0)). \quad (26)$$

If the sign of the coefficients does not change, and their magnitude fluctuates only within acceptable limits, the model is considered to be sufficiently stable.

In general, this procedure can be described by the condition

$$\Theta k \in \cap s,r,p,_{(}q_{)} \, \Omega(s,r,p,q). \quad (27)$$

The set $\Omega(s,r,p,q)$ reflects a set of permissible parameter values obtained under different options for normalizing indicators, weighting schemes and alternative specifications of the context vector. If the estimated parameters belong to their common domain, the calculation results do not critically depend on a specific model variant.

Fulfilling this condition means that the estimated dependencies between resource efficiency, CA and ESG performance are not an artifact of individual assumptions. This condition reflects a stable structural regularity suitable for analytical and managerial use.

The results obtained within the proposed model have a direct managerial interpretation. They can be used as an analytical basis for the implementation of ESG-oriented resource management in the agricultural sector, which is fully consistent with the topic and logic of the research. Their practical application is based on the transformation of quantitative estimates of the model into managerial signals, priorities and decision-making scenarios.

At the strategic management level, the parameters θ_E, θ_S and θ_G allow to quantitatively determine which areas of resource efficiency improvement make the greatest contribution to the corresponding components of ESG performance. This allows the management of agricultural enterprises to move from declaring the principles of sustainable development to a well-founded choice of strategic priorities. Here, the key guideline is investments in those resource practices that have the greatest multiplicative effect for ESG indicators.

At the tactical management level, the results of evaluating the coefficients $\varkappa_E$, $\varkappa_S$ and $\varkappa_G$ demonstrate the independent contribution of CA to increasing ESG performance, regardless of the level of resource efficiency. This makes it possible to substantiate management decisions regarding the phased implementation of digital resource monitoring systems, traceability systems and digital accounting.

Of key importance for management are the estimates of the coefficients μ_E, μ_S and μ_G, which quantitatively reflect the reinforcing role of CA in transforming resource flows into effective ESG indicators. In practice, this means that management decisions to improve resource efficiency should be made simultaneously with decisions to improve the quality of digital data. This is due to the fact that isolated measures in one of these areas have a limited effect. The model allows to determine the critical level of digital evidence, after which ESG management moves from formal to operational mode. At the micro level, the results of the model can be used to build internal systems of indicators and target benchmarks. The calculated indices of resource efficiency and digital data quality can be used as key performance indicators of divisions, cultures or production areas. This allows to integrate ESG goals into the operational management of production processes.

At the sectoral and regulatory levels, the model creates a basis for a differentiated policy to support the sustainable development of the agricultural sector. Quantitative assessments of the relationships between resource efficiency, CA and ESG performance allow the formation of incentive instruments focused on final indicators and the quality of management processes and data. This is especially important in the context of harmonization with EU requirements, where traceability, demonstrability and reproducibility of ESG information are key conditions for access to financial resources and markets.

The results of the model can be used as a basis for forming management decisions within the framework of an integrated system of ESG-oriented resource management. In this case, CA acts as a central link between the operational processes of agricultural production and the strategic goals of sustainable development.

The testing of the improved economic and mathematical model was carried out in the format of the sectoral time panel "Ukraine, t". This panel is an aggregated data set in which the unit of observation is the agricultural sector of the country as a whole, and the dynamics of indicators are analyzed over time (t = 2020–2024). All variables are formed exclusively on the basis of open official statistical sets. This approach corresponds to the logic of the research, within which the CA is interpreted as a tool for reproducible transformation of open resource flows into measurable ESG indicators suitable for management use.

The resource block of the model is formed on the basis of indicators held from the statistical set of the State Statistics Service of Ukraine [28–33]. The values of primary resource indicators for 2020–2024 are given in Table 7. It reflects the achievement of peak levels of resource intensity in 2021 and its subsequent sharp decline in 2022–2024.

Table 7

Indicators of resource intensity of mineral fertilizer application in agriculture of Ukraine, 2020–2024

Years	Application of mineral fertilizers, kg of fertilizer/ha	Share of areas treated with fertilizers, %
2020	134.9	79.6
2021	139.6	81.6
2022	101.0	61.7
2023	84.4	55.3
2024	84.9	56.8

Note: calculated according to [28]

At the next stage, the primary indicators were normalized using the min-max procedure within the sample of 2020–2024. After that, the integral index of resource efficiency of the sector RE_t was formed as the inverse aggregated function of normalized intensities. The weighting coefficients are set as $\alpha_F = 0.7$ and $\alpha_S = 0.3$, which reflects the higher analytical sensitivity of the indicator of fertilizer application per 1 ha compared to the indicator of area coverage. The results of normalization and the value of the resource efficiency index are given in Table 8.

Table 8

Normalized indicators of resource intensity and the resource efficiency index of the agricultural sector of Ukraine, 2020–2024

Years	zF_t	zS_t	Resource efficiency index (RE_t)
2020	0.781	0.681	0.082
2021	1.000	1.000	0.000
2022	0.255	0.278	0.716
2023	0.000	0.000	1.000
2024	0.006	0.049	0.977

Note: author's calculations based on data [28]

The obtained REt values quantitatively confirm the transition of the agricultural sector of Ukraine after 2021 to significantly lower resource intensity. At the same time, the correct interpretation of this effect requires a connection with the dynamics of output. This is due to the fact that the decrease in intensities during the war period may reflect structural and spatial limitations of production, and not exclusively an increase in technological efficiency.

To link resource efficiency with the performance of the sector, the research used the indicator of the volume of agricultural production in constant prices of 2016 Qt, million UAH. The agricultural production index $ISVt$ is considered in the work as an auxiliary dynamic indicator. It reflects the annual relative change in the volume of agricultural production and is used to restore aggregated absolute values of output in the absence of complete level statistical data. For 2020–2022, official level data from the State Statistics Service of Ukraine were used [29]. For 2023–2024, the value of Qt was restored by the index method based on agricultural product indices $ISVt$, % to the previous year [28–30]. On this basis, the resource intensity indicator per unit of output It, kg per 1 million UAH of output, was formed. In the sectoral dimension, it was used as an environmental proxy indicator (proxy) of ESG performance. The use of this indicator is due to the lack of complete and comparable sectoral environmental ESG indicators in open official sources. Therefore, resource intensity per unit of output is used as a quantitatively justified indirect measure of the environmental load of agricultural production and its performance.

The results are given in Table 9.

ISSN-L 2664-9969; E-ISSN 2706-5448

Table 9

Agricultural output and resource intensity per unit of output in Ukraine, 2020–2024

Years	Production volume, USD	Fertilizer intensity per output, kg/USD
2020	612121.5	9145.8
2021	712566.3	8130.3
2022	534380.3	7843.7
2023	593696.5	5899.6
2024	573510.8	6143.5

Note: calculated according to [28–32]

The quantitative results of Table 9 indicate a significant decrease in resource intensity per unit of output in 2023–2024 compared to the pre-war period. Within the model, this is interpreted as an improvement in the environmental component of ESG, provided that output is relatively stabilized.

A generalized interpretation of the results of the approbation for the management purposes of ESG-oriented resource management is systematized in Table 10.

Table 10

A generalized interpretation of the results of the approbation of the model for ESG-oriented resource management

Periods	Resource efficiency characteristics	ESG Interpretation
2020–2021	High resource intensity	Increased environmental risk
2022	A sharp decrease in intensities	Adaptive transformation
2023–2024	Minimal resource intensity	ESG optimization potential

Note: summarized by the author based on Tables 7–9

To complete the full architecture of the methodology, the testing was supplemented by the operationalization of the digital data quality index *DQt* and the consolidation of all input and calculation indicators into a single system (Table 11). The *DQt* index is formed as a composite of completeness, regularity, and level of data detail, which allows to record the CA as a measured factor, rather than a declarative characteristic.

Table 11 shows a consistent picture of the transformation of resource flows in the agricultural sector of Ukraine in 2020–2024. This allows to quantitatively trace the relationship between resource intensity, economic performance and digital evidence of data within the proposed model.

First of all, a stable inverse relationship is observed between resource intensity and the integral resource efficiency index RE_t. With an increase in F_t and S_t in 2020–2021, the RE_t index acquires minimum values of 0.081 and 0.000. The reduction in fertilizer application is accompanied by an increase in RE_t. The decrease in F_t in 2023–2024 by almost 40% compared to 2021 corresponds to an increase in the resource efficiency index by almost one unit of the normalization scale. This confirms the hypothesis of the nonlinear nature of the relationship, which is embedded in the model, in which the effect of reducing intensities increases when a certain threshold level is reached. The second key relationship is between the resource efficiency index RE_t and the resource intensity indicator per unit of output I_t. Within the framework of sectoral testing, it is used as an environmental proxy for ESG performance. In 2020–2021, low RE_t values are combined with high I_t values at the level of 9145.8–8130.3 kg/USD, while in 2023–2024, with RE_t close to 1, the intensity of It decreases to 4685.1–4657.0 kg/USD. RE_t by 0.9–1.0 conventional units is associated with a decrease in resource load per unit of output by approximately 3500–4500 kg/million USD. This corresponds to a reduction of almost half from the 2020 level. Such dynamics indicate the presence of an economically significant relationship between the resource behavior of the sector and the environmental component of ESG.

The interaction between resource efficiency and output *Qt* requires a separate analytical emphasis. The data in Table 11 show that in 2022, the increase in *REt* to 0.738 is accompanied by a drop in *Qt* to 534,380.3 USD, which indicates the dominance of external production constraints. In 2023–2024, the situation changes: while maintaining high values of *REt*, the output volume is restored to 747,598.0–756,569.2 USD, and the *It* intensity continues to decrease. This allows to interpret the relationship between *REt* and *Qt* as conditionally complementary in the medium term, when the reduction in resource pressure is no longer accompanied by a proportional loss of economic output.

The CA role in shaping these relationships is manifested through the digital data quality index *DQt*. High *DQt* values at 0.90 in 2020–2022 and 0.80 in 2023–2024 ensure comparability of indicators over time. They also allow to interpret the identified dependencies as structural, rather than statistically random. A decrease in *DQt* in 2023–2024 does not lead to a break in the relationship between *REt* and *It*. This indicates its stability and confirms the feasibility of using lag variables and integral indices in the model.

Summarizing the results of the testing, it can be noted that in 2020–2024, the reduction in the application of mineral fertilizers and cultivated areas was accompanied by an increase in the integral resource efficiency index from 0.081 to 0.967 (by more than 11.9 times) and a simultaneous decrease in the resource intensity of production from more than 9000 to about 4600 kg/USD (by approximately 49%). This corresponds to an average annual decrease in resource load of about 10–12% and indicates a significant increase in resource efficiency.

Table 11

Input data and calculation indicators for testing the model in the agricultural sector of Ukraine, 2020–2024

Years	Minimum fertilizer application F_t, kg of nutrients/ha	Share of areas treated with fertilizers S_t, %	Agricultural land area A_t, million ha	Agricultural output Q_t, USD	Agricultural output index ISV_t, % to the previous year	zF_t	zS_t	Resource efficiency index RE_t	Fertilizer intensity per output I_t, kg/USD	Digital data quality index DQ_t
2020	134.9	79.6	41.5	612121.5	98.5	0.781	0.681	0.081	9145.8	0.90
2021	139.6	81.6	41.5	712566.3	114.4	1.000	1.000	0.000	8130.3	0.90
2022	101.0	61.7	41.5	534380.3	73.8	0.255	0.278	0.738	7843.7	0.90
2023	84.4	55.3	41.5	747598.0	139.9	0.000	0.000	1.000	4685.1	0.80
2024	84.9	56.8	41.5	756569.2	101.2	0.023	0.057	0.967	4657.0	0.80

Note: calculated according to [33–35]

At the same time, the restoration of production volumes in 2023–2024 occurs at a significantly lower level of resource load. The integral index varied within 0.081–0.967 (amplitude 0.886), which reflects a structural shift in resource use. Achieving values of more than 0.9 indicates the transition of the system to a high efficiency zone. At the same time, the decrease in resource intensity below the conditional threshold level (≈5000 kg/USD) is accompanied by an accelerated increase in efficiency.

In general, the results of the approbation allow to identify a stable inverse relationship between resource intensity and the efficiency of the functioning of the agricultural sector, which is manifested in the growth of the corresponding integral index. The revealed nonlinear nature of this relationship is strengthened under conditions of increasing digital evidence of data and is consistent with the conceptual logic of the constructed economic and mathematical model and the assessment of cause-and-effect relationships within the ESG approach.

3.5. Discussion of the research results

The conducted research allows to look at the role of ESG in the activities of agricultural enterprises in a slightly different way. Until relatively recently, these approaches were mostly associated either with the preparation of non-financial reporting or with the need to meet external regulatory requirements. At the same time, the results obtained show that ESG is gradually beginning to be integrated into the internal logic of enterprise management. In particular, it can be noted that the use of digital analytics changes the nature of the application of ESG indicators: they cease to be formal and are increasingly used as a tool in the process of making managerial decisions. This is manifested in the possibility of directly linking sustainable development indicators with data on the use of resources (land, water, energy), which increases the analytical value of such indicators in the decision-making process.

The obtained empirical results confirm the presence of a stable relationship between resource efficiency, economic performance and ESG performance. In this case, the quality of digital data plays a key role, which determines the possibility of interpreting the identified dependencies as structural, rather than random. Thus, ESG management in combination with digital analytics should be considered as a tool for improving the efficiency of resource management, which allows to reconcile economic results with environmental and social parameters of agricultural enterprises. The results obtained generally correlate with modern research, in which more and more attention is paid to the role of digital technologies in the development of the agricultural sector. In recent years, digitalization has increasingly been considered as one of the key factors that can affect both environmental indicators and the economic efficiency of agribusiness. At the same time, most works analyze these issues separately – either in the context of ESG, or from the point of view of digital transformation. This research attempts to combine these approaches, considering them not in isolation, but in connection – through resource flows, data analytics and ESG results. However, the results once again highlight a problem that has already been highlighted by other authors: in practice, ESG often remains fragmented, and the link between production data and sustainability indicators is not always clearly established. In this sense, the proposed approach attempts to partially close this gap by showing how such data can be systematically linked. Interestingly, the results do not confirm the widespread assumption of a contradiction between environmental requirements and economic results. On the contrary, with proper digital support, these aspects can mutually reinforce each other. Overall, it is possible to say that the conclusions obtained do not contradict existing scientific approaches, but complement them, focusing on the practical combination of digital analytics and ESG in the process of resource management.

The results obtained should not be perceived as absolutely universal, as they have certain limitations. First, the analysis was conducted at the level of the entire sector, which does not always allow to see real differences between individual enterprises. In fact, they can differ significantly – both in terms of technology, the level of digitalization, and how efficiently they use resources. Second, the use of the resource intensity indicator is explained by the fact that complete non-financial data is simply not always available. This allows to perform calculations and preserve their logic, but at the same time some of the ESG aspects are actually left out of consideration. It is also worth considering that for certain periods, the dynamics of production were restored using indices. This is a normal approach, but it may slightly affect the accuracy of the estimates of the relationships between indicators. External factors should also be taken into account separately. They are only partially taken into account in the model, so it was not possible to completely "cleanse" the results of their influence. As a result, this means that the conclusions obtained are better viewed as a generalized assessment at the industry level. For more accurate results, analysis is required at the level of specific enterprises.

To identify a more accurate impact of CA on ESG management results, future studies should take into account the quality of data and the level of digitalization of enterprises. This requires paying attention to climatic features in different regions, the time horizon of data analysis and forecasting changes in indicator values. In addition, it is also necessary to deepen the list of indicators by agricultural production technologies.

4. Conclusions

1. An analysis of scientific approaches to ESG resource management in the agricultural sector has been performed. The research results confirm that the implementation of sustainable development values in the agricultural sector requires a transition to ESG-oriented resource management based on CA. Analytical generalization of scientific approaches shows that most of the existing models are fragmentary. They do not provide a direct and reproducible connection between resource flows and ESG management indicators. This is confirmed by the results of indicator-oriented, risk-oriented and regional studies. The research substantiates the system-forming role of CA in the transformation of resource flows of agricultural enterprises into measurable ESG management indicators. CA ensures the unification of resource data, their analytical processing, traceability and reproducibility of results in the medium-term dynamics. This is confirmed by conceptual studies of the digital transformation of agribusiness and corporate and institutional examples for the period 2020–2024. As a result, ESG can be used as a basis for management decisions regarding the choice of technologies; investment priorities and production structure, and not be limited to the function of non-financial reporting.

2. It has been found that the use of digital tools allows for the formalization of disparate production data in the form of ESG indicators. It has been found that this becomes possible by combining sensor measurements, satellite observations and internal accounting systems. Its combination makes it possible to calculate indicators. It was noted that a number of indicators can be determined regularly in a formalized form, which is important for analyzing dynamics. In the agricultural sector, in the period 2020–2024, there was an active application of digital platforms, which made it possible to monitor and predict agro-risks and resource efficiency. It has been established that in the field of digital agriculture, the practice of using digital tools in corporate management systems is being scaled up.

3. A mechanism for integrating resource data and ESG indicators into an integrated agrarian business management system has been developed. The sequence of stages of the integration mechanism has been highlighted, and their content has been characterized through their functional place in the management system of agricultural enterprises. The content characteristics of the highlighted stages indicate that the

ISSN-L 2664-9969; E-ISSN 2706-5448

integration of resource data and ESG indicators into the management system is possible exclusively on the basis of ensuring compliance between resources and indicators. This compliance can be achieved through binding to a specific type of resource, a clear method of calculation and further use of the results when assessing the enterprise's activities. When these conditions are met, the indicators become more transparent for verification and understandable for analysis. This facilitates control of the results, increases confidence in the data obtained and makes them useful for management decisions in agricultural companies. The issue of the reliability of such indicators is of particular importance in the context of increasing requirements from regulators and investors. This is due to the spread of CSRD standards and the development of digital traceability systems for supply chains.

The research suggests that the implementation of ESG-oriented resource management in the agricultural sector of Ukraine will be gradual. This is due to the need to harmonize internal practices of enterprises with the regulatory requirements of the European Union and international approaches to sustainable development. Among the areas that are gaining the greatest importance are adaptation to CSRD requirements, the development of digital tools for traceability of land use in accordance with the EUDR regulation. The possibility of using analytics to assess the efficiency of resource use should be highlighted separately. An important task is also the gradual inclusion of ESG indicators in the system of management decisions of agricultural enterprises. In this context, digital analytics opens up new opportunities for Ukrainian agricultural business. It allows combining the restoration of production potential with the requirements of European markets and increasing investor interest due to more transparent and comparable performance results.

4. A model for assessing the relationship between the efficiency of resource use and the effectiveness of ESG indicators has been developed. According to the results of the developed model, it was established that the relationship between the efficiency of resource flow use of agricultural enterprises and the effectiveness of ESG indicators has a structural and dynamic nature. It is formed under the joint influence of resource behavior and the quality of digital data. The proposed model allows to quantitatively separate the effects of resource efficiency, target audience and contextual conditions, and formalize their complementary interaction. It has been proven that ESG performance is not an autonomous characteristic, but is derived from the manageability of resource flows in a digital analytical environment. Testing the model on materials from the agricultural sector of Ukraine for 2020–2024 confirmed its applicability for the analysis of ESG-oriented resource management at the sectoral level. It also showed a robust quantitative relationship between reducing resource intensity, restoring economic output and improving environmental proxy ESG performance. The results show that, given sufficient numerical evidence, reducing resource burden does not contradict the economic viability of the sector. Reducing resource burden serves as the basis for developing a balanced model of sustainable development, consistent with EU requirements and modern ESG management logic.

Conflict of interest

The authors declare that they have no conflict of interest in connection with the current research, including financial, personal, authorial or any other that could influence the research and results presented in this article.

Financing

The research was conducted without financial support.

Data availability

All data are available in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that no artificial intelligence technologies were used in the creation of the current paper.

Authors' contributions

Oleh Kniaz: Conceptualization, Methodology, Validation, Project administration; ***Petro Pererva:*** Investigation, Resources, Data curation, Supervision; ***Nelli Heorhiadi:*** Writing – review and editing; ***Roksolana Vilhutska:*** Software, Visualization; ***Khrystyna Peredalo:*** Formal analysis, Writing – original draft.

References

1. Freeman, R. E. (1984). *Strategic management: a stakeholder approach.* Boston: Pitman. Available at: https://archive.org/details/strategicmanagem00free
2. *Our common future* (1987). World Commission on Environment and Development. Oxford: Oxford University Press, 383. Available at: https://www.academia.edu/10711693/Our_common_future_By_World_commission_on_environment_and_development_London_Oxford_University_Press_1987_pp_383_5_95_
3. Porter, M. E., Linde, C. (1995). Toward a New Conception of the Environment-Competitiveness Relationship. *Journal of Economic Perspectives, 9 (4),* 97–118. https://doi.org/10.1257/jep.9.4.97
4. Elkington, J. (1997). *Cannibals with forks: The triple bottom line of 21st century business.* Oxford: Capstone. Available at: https://www.scirp.org/reference/referencespapers?referenceid=2092269
5. Sustainability reporting guidelines (2000). *Global Reporting Initiative.* Available at: https://www.globalreporting.org/standards/gri-standards-download-center
6. Porter, M. E., Kramer, M. R. (2011). Creating shared value. *Harvard Business Review, 89 (1–2),* 62–77. Available at: https://hbr.org/2011/01/the-big-idea-creating-shared-value
7. Kniaz, S., Kosovska, V., Shayda, O., Novosad, Z., Yaremko, L., Fedyuk, V. (2021). Method of Selection of Indicators in the Context of Information and Analytical Support of Evaluation of Development of Foreign Economic Activity of Enterprises. *2021 11th International Conference on Advanced Computer Information Technologies (ACIT).* Deggendorf: IEEE, 389–392. https://doi.org/10.1109/acit52158.2021.9548613
8. Mysiuk, R. V., Yuzevych, V. M., Yasinskyi, M. F., Kniaz, S. V., Duriagina, Z. A., Kulyk, V. V. (2022). Determination of conditions for loss of bearing capacity of underground ammonia pipelines based on the monitoring data and flexible search algorithms. *Archives of Materials Science and Engineering, 115 (1),* 13–20. https://doi.org/10.5604/01.3001.0016.0671
9. Kniaz, S., Brych, V., Marhasova, V., Tyrkalo, Y., Skrynkovskyy, R., Sumets, A. (2022). Modeling of the Information System of Environmental Risk Management of an Enterprise. *2022 12th International Conference on Advanced Computer Information Technologies (ACIT).* Ruzomberok: IEEE, 215–218. https://doi.org/10.1109/acit54803.2022.9912743
10. Yap, C. K., Leow, C. S. (2023). Environment, social and governance in sustainable agricultural practices in developing countries: A short note. *Sustainable Social Development, 1 (3).* https://doi.org/10.54517/ssd.v1i3.2337
11. Julkovski, D. J., Sehnem, S., Stenger, E. A. F. (2023). ESG guidelines for agribusiness. *Revista Pensamento Contemporâneo Em Administração, 17 (4),* 74–89. https://doi.org/10.12712/rpca.v17i4.60261
12. Kniaz, S., Podolchack, N., Dziurakh, Y., Karkovska, V., Kucher, A. (2023). Development of government regulation on investment activities in agriculture of Ukraine. *Economic Studies, 32 (2),* 136–150. Available at: https://ideas.repec.org/a/bas/econst/y2023i2p136-150.html
13. Annosi, M. C., Appio, F. P., Brenes, E. R., Brunetta, F. (2024). Exploring the nexus of digital transformation and sustainability in agribusiness: Advancing a research agenda. *Technological Forecasting and Social Change, 206,* 123587. https://doi.org/10.1016/j.techfore.2024.123587
14. Huseynli, J., Huseynov, Y., Totubaeva, N., Guliyev, M., Azizova, G. (2024). The role of ESG in the adaptation of the agro-industrial sector to climate change. *Scientific Horizons, 27 (5),* 131–142. https://doi.org/10.48077/scihor5.2024.131
15. Hopka, M., Kovtun, O. (2024). Features of implementation of ESG management criteria in Ukrainian agriculture in the context of global challenges and EU integration. *Biological Systems: Theory and Innovation, 15 (3),* 87–99. https://doi.org/10.31548/economics/3.2024.87
16. Yap, C. K., Al-Mutairi, K. A. (2024). A Conceptual Model Relationship between Industry 4.0 – Food-Agriculture Nexus and Agroecosystem: A Literature Review and Knowledge Gaps. *Foods, 13 (1),* 150. https://doi.org/10.3390/foods13010150

17. Kniaz, S., Brych, V., Heorhiadi, N., Shevchenko, S., Dzvonyk, R., Skrynkovskyy, R. (2024). Enhancing the Informativeness of Managing Mentoring Activities based on Simulation Modeling. *2024 14th International Conference on Advanced Computer Information Technologies (ACIT)*. Ceske Budejovice: IEEE, 8, 384–388. https://doi.org/10.1109/acit62333.2024.10712547

18. Kniaz, S., Brych, V., Heorhiadi, N., Shevchenko, S., Dzvonyk, R., Skrynkovskyy, R. (2024). Informational-Reflective Management of Mentoring Activities Development in the Enterprise. *2024 14th International Conference on Advanced Computer Information Technologies (ACIT)*. Ceske Budejovice: IEEE, 13, 389–392. https://doi.org/10.1109/acit62333.2024.10712601

19. Witt, N., Thorsøe, M. H., Graversgaard, M. (2025). ESG reporting meets farmer – implications of the European corporate sustainability reporting directive for the agrifood sector. *British Food Journal, 127 (13),* 264–283. https://doi.org/10.1108/bfj-01-2024-0110

20. Mutswiri, P. (2025). ESG integration and sustainability in African agribusiness: A review of challenges, practices and impacts. *The Dyke, 19 (1),* 667–687. https://doi.org/10.64754/thedyke.v19i1.490

21. Alsanhani, A. N., Al-Shayaa, M. S., Dabiah, A. T., Alfridi, J. S. (2025). Advancing Sustainable Agriculture Through Digital Technology: The Role of the Agricultural Guide App in Improving Olive Farming Practices in Saudi Arabia. *Sustainability, 17 (6),* 2340. https://doi.org/10.3390/su17062340

22. Greenhouse gas emissions from agrifood systems: Global, regional and country trends 2000–2022 (2024). *Food and Agriculture Organization of the United Nations.* Available at: https://www.fao.org/statistics/highlights-archive/highlights-detail/greenhouse-gas-emissions-from-agrifood-systems.-global--regional-and-country-trends--2000-2022/en

23. Deforestation Regulation implementation: Traceability and geolocation of commodities subject to EUDR (2024). *European Commission.* Available at: https://green-forum.ec.europa.eu/nature-and-biodiversity/deforestation-regulation-implementation/traceability-and-geolocation-commodities-subject-eudr_en

24. *Strategy Report: Annual Report 2021* (2021). Olam Group Limited. Available at: https://www.olamgroup.com/content/dam/olamgroup/investor-relations/ir-library/annual-reports/annual-reports-pdfs/2021/olam_strategy_report_2021.pdf

25. Impact Report 2024 (2024). *Cargill.* Available at: https://www.cargill.com/sustainability/doc/1432271051366/2024-impact-report-summary.pdf

26. Bayer Sustainability Report 2022 (2023). *Bayer.* Available at: https://www.bayer.com/sites/default/files/2023-02/Bayer-Sustainability-Report-2022.pdf

27. DATA-DRIVEN DIGITAL AGRICULTURE. (2021). *World Bank.* Available at: https://thedocs.worldbank.org/en/doc/1a163904ccb86646bf2e5d3d6f427f3d-0090012023/related/WB-DDAG-FA-web.pdf

28. Use of inorganic and organic fertilizers, use of pesticides (1990–2024). (2024). *State Statistics Service of Ukraine.* Available at: https://www.ukrstat.gov.ua/operativ/operativ2021/sg/vmod90_20ue.xls

29. Agricultural productionin in 2016 constant prices 2022. (2022). *State Statistics Service of Ukraine.* Available at: https://ukrstat.gov.ua/operativ/operativ2022/sg/psg_pc/pcg_pc_22_ue.xlsx

30. Agricultural production at constant prices. (2024). *State Statistics Service of Ukraine.* Available at: https://www.ukrstat.gov.ua/operativ/operativ2017/sg/pro_sg/arch_pro_sg_p_e.htm

31. *Indices of agricultural production (1991–2024).* (2024). State Statistics Service of Ukraine. Available at: https://www.ukrstat.gov.ua/operativ/operativ2020/sg/sg_rik/arch_iosv_e.htm

32. Indices of agricultural production. (2024). *State Statistics Service of Ukraine.* https://www.ukrstat.gov.ua/operativ/operativ2020/sg/ivp/arch_ivp20e.htm

33. Food and Agriculture Organization of the United Nations. *FAOSTAT.* Available at: https://www.fao.org/faostat/en/#data/RFN

34. Common agricultural policy overview. *European Commission.* Available at: https://agriculture.ec.europa.eu/common-agricultural-policy/cap-overview_en

35. Indeksy sil's'kohospodars'koyi produktsiyi (2010–2024). *Holovne upravlinnya statystyky u Kharkivs'kiy oblasti.* Available at: https://kh.ukrstat.gov.ua/indeksy-obsiahu-silskohospodarskoho-vyrobnytstva

✉ ***Petro Pererva,*** *Doctor of Economic Sciences, Professor, Department of Business Economics and International Economic Relations, National Technical University "Kharkiv Polytechnic Institute", Kharkiv, Ukraine, e-mail: pgpererva@gmail.com, ORCID: https://orcid.org/0000-0002-6256-9329*

Oleh Kniaz, *PhD, Department of Entrepreneurship and Environmental Expertise of Goods, Lviv Polytechnic National University, Lviv, Ukraine, ORCID: https://orcid.org/0009-0006-0442-9711*

Nelli Heorhiadi, *Doctor of Economics, Professor, Department of Management and International Entrepreneurship, Lviv Polytechnic National University, Lviv, Ukraine, ORCID: https://orcid.org/0000-0002-8348-5458*

Roksolana Vilhutska, *PhD, Associate Professor, Department of Management and International Entrepreneurship, Lviv Polytechnic National University, Lviv, Ukraine, ORCID: https://orcid.org/0000-0002-9291-8606*

Khrystyna Peredalo, *PhD, Associate Professor, Department of Foreign Economic and Customs Activities, Lviv Polytechnic National University, Lviv, Ukraine, ORCID: https://orcid.org/0000-0001-5840-9210*

✉ *Corresponding author*