

CONCEPTUAL APPROACHES AND CURRENT TRENDS IN RESEARCH ON SUSTAINABLE DEVELOPMENT OF THE AGRICULTURAL SECTOR

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The agricultural sector plays a decisive role in global food production and, on this basis, in ensuring the global food security system, environmental sustainability, and livelihoods in rural areas. However, intensive agricultural practices have led to numerous environmental and social problems, including climate change; high rates of biodiversity loss; land degradation due to erosion, compaction, salinization, and soil contamination; depletion and pollution of water resources; socioeconomic inequality in rural areas and population decline [1; 2; 3; 4; 5; 6], with the agricultural sector itself generating these problems in a significant number of cases [7].

Sustainable development of the agricultural sector aims to address these problems by establishing mechanisms that will promote environmentally sound, socially just, and economically viable agricultural systems. In this context, there is a need to examine the dynamic aspects and substantive characteristics of the concept of “sustainable development of the agricultural sector” and, on this basis, to formulate an author’s definition.

A dynamic analysis was conducted based on data from Google Trends and the number of publications in the SCOPUS database related to the topic of sustainable development of the agricultural sector (Fig. 1).

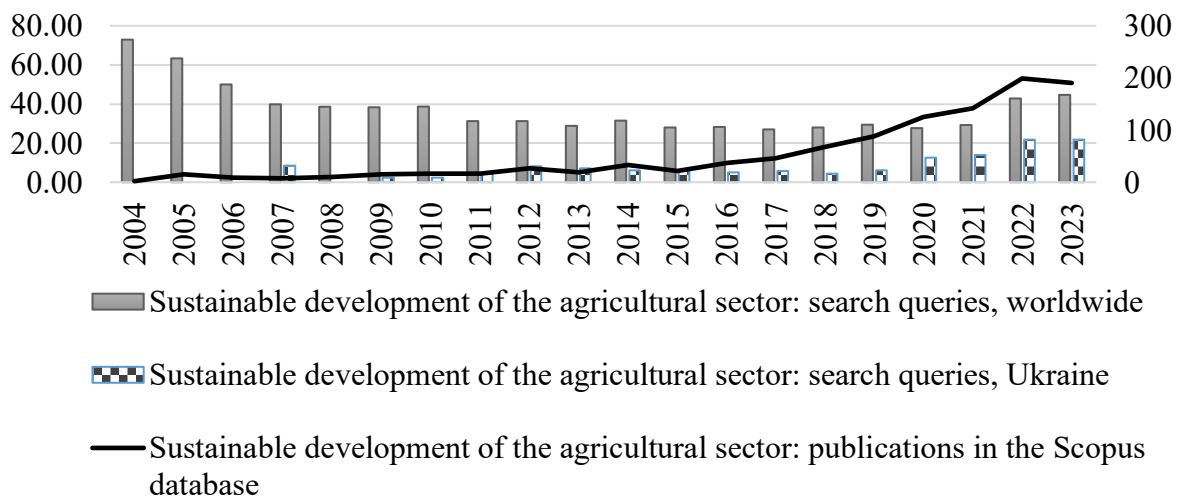


Figure 1. Comparison of the dynamics of Google search queries on sustainable development of the agricultural sector and scientific publications in the SCOPUS scientometric database on the same topic for 2004-2023.

Note: The annual average index for each term was calculated by averaging the indices for all months of each year.

Source: compiled by the author

Google Trends data covers global and Ukrainian search queries, while data from the international SCOPUS scientometric database covers the number of academic publications on this topic. The purpose of the analysis is to identify trends in user interest in the sustainable development of the agricultural sector and the correlation between this interest and academic research.

The global search query index shows high values at the beginning of the study period, particularly in 2004 (72.92), with a gradual decline to a low point in 2017 (27.00). Since 2018, there has been a rise in user interest in this topic, peaking in 2023 (44.67). This indicates growing attention to sustainable development in the agricultural sector in recent years. The Ukrainian search query index was zero until 2007, indicating a low level of interest in this topic in Ukraine during that period. Since 2007, user interest has been gradually increasing, reaching a peak in 2022 (21.92). This indicates a growing awareness of the importance of ensuring sustainable development in Ukraine’s agricultural sector. The number of publications in the international

scientometric database SCOPUS on the topic of sustainable development in the agricultural sector has increased year by year, reaching a peak of 199 publications in 2022. It is worth noting that in 2022, when the number of search queries reached a high (42.83), the number of publications also peaked (199).

Figure 2 shows the trend in the frequency of use of the phrase “sustainable development of agriculture” in books indexed by Google for the period from 2004 to 2018.



Figure 2. Results of the analysis of the frequency of mentions of the term “sustainable development of agriculture” published in English-language books worldwide from 2004 to 2018
Source: created by the author using the Google Books Ngram Viewer tool

Based on the graph’s amplitude, several stages of scientific interest in issues related to ensuring the sustainable development of the agricultural sector can be identified, namely: 2004-2012 - the stage of emerging interest, confirmed by an increase in the frequency of the phrase’s use; 2012-2015 - a stage of waning interest, with the frequency of the phrase’s use declining slightly; 2015-present - a stage of renewed interest in the sustainable development of the agricultural sector, confirmed by a new increase in the frequency of the phrase’s use.

Thus, based on the study’s findings, we can conclude that there has been a significant increase in interest in the sustainable development of the agricultural sector among both internet users and in academic circles. A substantial increase in attention to this topic has been observed since 2015, when the UN General Assembly adopted the resolution “Transforming our world: the 2030 Agenda for Sustainable Development.” This document, in particular, identified Goal 2-“Ensure food security, improve nutrition, and promote sustainable agriculture”-as one of the key goals directly related to the sustainable development of the agricultural sector.

The next stage of the study is a contextual and bibliometric analysis of the concept of sustainable development of the agricultural sector.

Based on the results of our review of the scientific literature, we have determined that both the concept of sustainable development of the agricultural sector and the concept of a “sustainable agricultural sector” (“sustainability of the agricultural sector”) are widely studied in the scientific literature, and while they are often used as synonyms, in our view, they have different meanings and implications. Understanding these differences is crucial for formulating effective policies and strategies to achieve sustainable development goals in the agricultural sector.

Given the above, to achieve the research objective, we consider it appropriate to summarize the findings of domestic and foreign scholars in this field and distinguish between these concepts.

Approaches to interpreting the concept of “sustainability of the agricultural sector” are presented in Table 1.

Sustainability is a systemic property that arises in the agricultural sector as a result of numerous social, environmental, economic, and physical interactions within it and in interaction with the external environment [8], and characterizes the system’s ability to withstand and maintain its functions over time.

Table 1. Approaches to understanding the concept of “sustainability of the agricultural sector” [compiled by the author based on 9; 10; 11; 12; 13; 14; 15; 16; 17; 18]

Source	Definition of the concept of “sustainability of the agricultural sector”
Martsynuk N. M.	a sector that produces a sufficient quantity of high-quality food, conserves its resources, is environmentally safe, and generates profits.
Stoyanets N. V.	a system of production, processing, marketing, and consumption of agricultural products that is optimally organized in terms of the use and regeneration of socio-ecological and economic resources, and which is supported by economic agents as well as institutions authorized to develop and implement strategic and operational state policies in the field of agriculture, the ultimate goal of which is to achieve the country’s food security
Brodts S. et al.	a sector that ensures the achievement of environmental protection, economic profitability, and social justice
Pretty J.	includes the concepts of both resilience (the ability of systems to withstand shocks and stresses) and longevity (the ability of systems to continue to exist over a long period of time), and encompasses much broader economic, social, and environmental outcomes.
Smith E., Serna I.	maximizing food production while minimizing environmental impact ... involves preserving the environment, expanding natural resources, and creating a better life for animals and people, ensuring the long-term sustainability of food sources while reducing dependence on conventional farming methods and providing alternative food options.
Streimikis, J., Balezentis, T.	A system that allows farms of all sizes to be profitable and contribute to the local economy, ensuring the effective management of the natural systems and resources on which farms depend. ... supports the next generation of farmers, treats workers fairly, promotes racial equality and justice, ensures access to healthy food for all, and puts people and communities above corporate interests.
Shelef O. et al.	the use of biological resources for the production of food and fiber, among other products, taking into account environmental impacts
Food and Agriculture Organization of the United Nations	adherence to the principles of sustainable food and agriculture: improving resource efficiency; conserving, protecting, and enhancing natural ecosystems; protecting and improving living conditions and social well-being in rural areas; enhancing the resilience of people, communities, and ecosystems; promoting the effective management of both natural and human systems.
	ensures that agricultural products meet, in terms of both quantity and quality, the nutritional needs of current and future generations; provides long-term employment, adequate income, and decent living and working conditions for all those engaged in agricultural production; contributes to maintaining and even increasing the productivity of natural resources as well as the regenerative capacity of renewable resources, without disrupting key ecological cycles and the natural balance, destroying the socio-cultural characteristics of rural communities, or causing environmental pollution; reduces the agricultural sector’s vulnerability to adverse natural and socio-economic factors and other risks, and strengthens producers’ confidence in their own capabilities
American Agronomic Association	over the long term, improves the state of the environment and natural resources on which agricultural activity depends; meets human needs for food and plant-based raw materials; is economically viable and improves the quality of life for farmers and society as a whole
U.S. Farm Bill	an integrated system of crop and livestock production aimed at the following long-term goals: meeting human needs for food and plant-based raw materials; improving the condition of natural resources on which agriculture depends; ensuring the most efficient use of non-renewable resources and internal

By synthesizing the approaches of the above-mentioned and other scholars, we have identified the following key parameters through which the concept of “sustainability of the agricultural sector” is examined (Fig. 3): as a capacity, as a system of long-term goals, as a set of specific characteristics, and as a specific state, which can be considered both at the micro level (the level of an individual producer) and at the macro level (the level of the agricultural sector).

In addition to various approaches to interpreting the concept of “sustainability of the agricultural sector,” researchers emphasize different aspects (dimensions) of it in their definitions.

All presented approaches include elements of conservation and improvement of natural resources, and reduction of environmental impact (Stoyanets N. V., Martsynuk N. M., Smith E. and Serna I., Pretty J., Shelef

O., and others; legislation in the field of sustainable development). Accordingly, the environmental aspect is key in the context of developing mechanisms to ensure the sustainability of the agricultural sector. A number of approaches emphasize the importance of ensuring social justice and improving living and working conditions in rural areas (Brodt S. et al., Pretty J., Stoyanets N. V., N. M. Martsynuk, the Food and Agriculture Organization of the United Nations, the American Society of Agronomy, etc.), which underscores the significance of the social aspect.

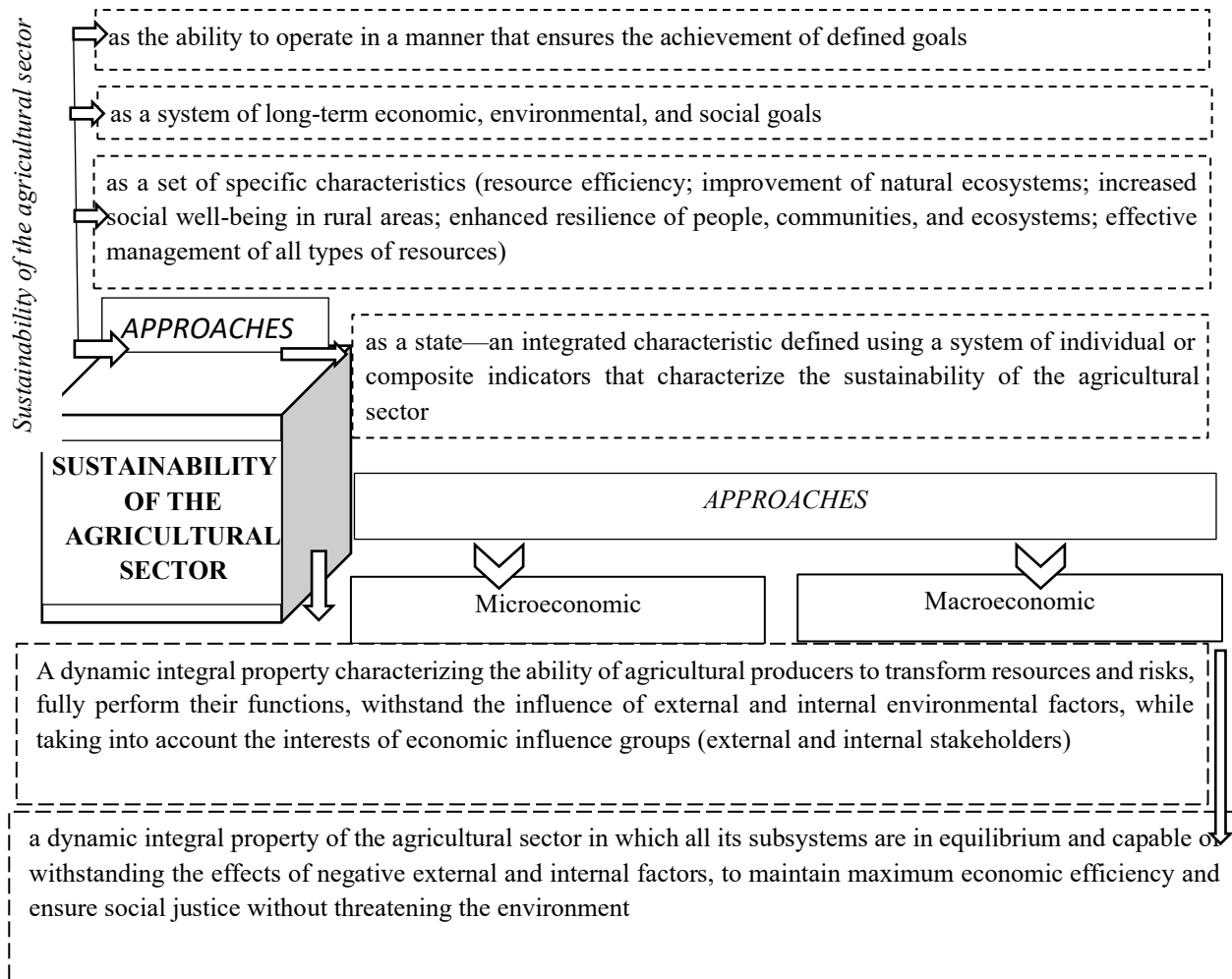


Figure 3. Summary of approaches to defining the concept of “sustainability of the agricultural sector”
 Source: compiled by the author

A number of definitions of sustainability in the agricultural sector include the aspect of economic feasibility and profitability (S. Brodt, N. M. Martsynuk, American Society of Agronomy). At the same time, in some cases, the emphasis is placed on the efficient use of both natural and human resources (Shelef O., Food and Agriculture Organization of the United Nations, American Society of Agronomy). Accordingly, the measure of sustainable development in the agricultural sector is an adequate level of economic efficiency.

The concepts of system resilience and longevity are defined in the approaches of Pretty J., Smith E., and Serna I. of the Food and Agriculture Organization of the United Nations, which underscore the need for long-term planning and adaptability of agricultural systems.

To summarize the above, we propose considering the sustainability of the agricultural sector through a comprehensive approach in both quantitative and qualitative aspects, as presented in Figure 4.

Therefore, we propose considering the sustainability of the agricultural sector comprehensively—using both qualitative (as capacity and as a state of being) and quantitative (as a structural concept characterized by a system of indicators) approaches across three main dimensions (environmental, economic, and social). The environmental dimension emphasizes the capacity to preserve the environment and use natural resources

efficiently. The economic dimension highlights the capacity to maintain a certain level of economic production indefinitely. The social dimension concerns the capacity to function at a defined level of social well-being for an indefinite period.

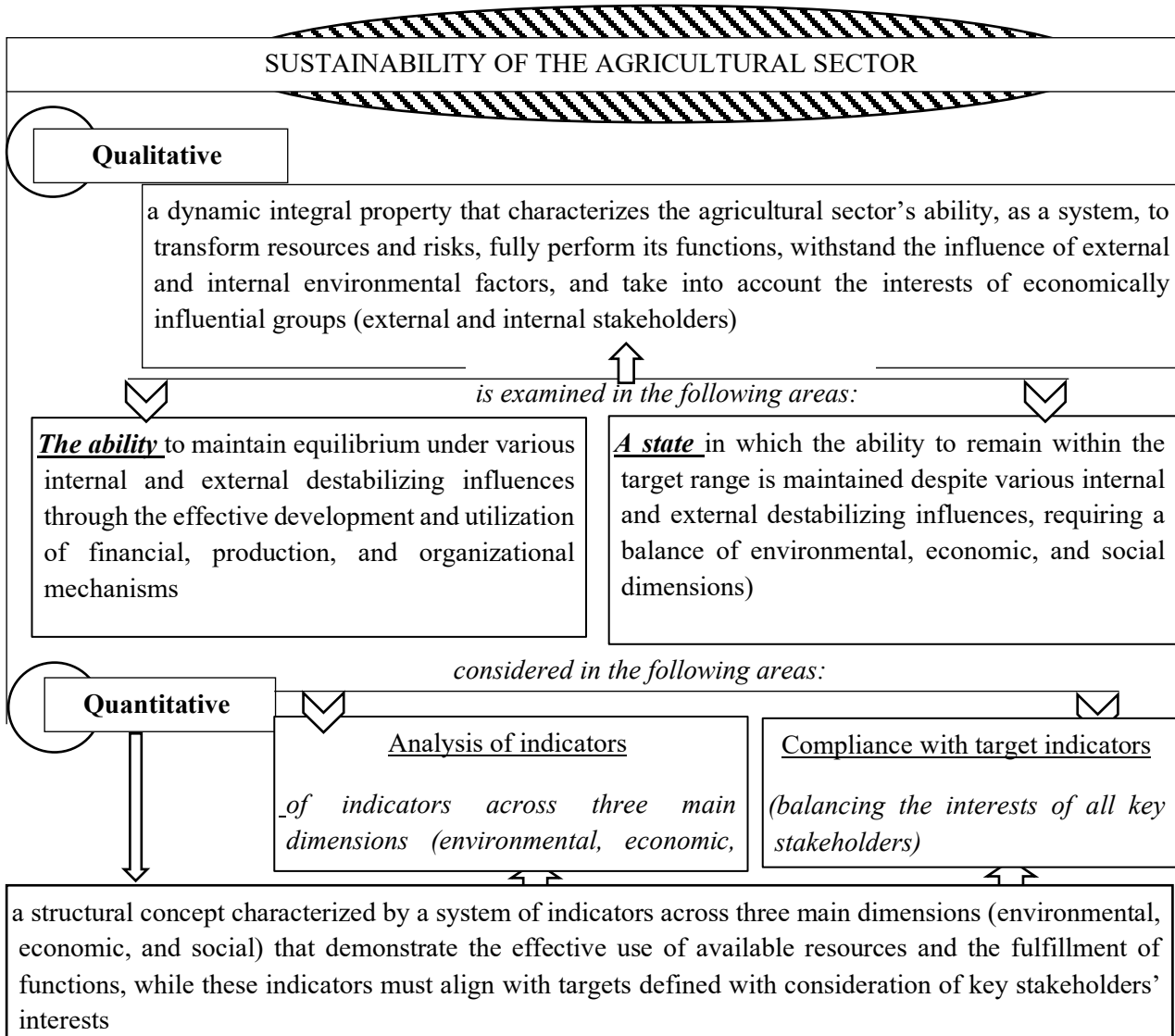


Figure 4. A comprehensive approach to the concept of “sustainability of the agricultural sector”

Source: Compiled by the author

Approaches to interpreting the concept of “sustainable development of the agricultural sector” are presented in Table 2.

Table 2. Approaches to understanding the concept of “sustainable development of the agricultural sector” [compiled by the author based on 18; 19; 20; 21; 22; 23; 24; 25; 26; 27]

Source	Definition of the concept of “sustainable development of the agricultural sector”
<i>Ability</i>	
Varchenko O. M., Danilenko A. S.	of an economic entity to dynamically maintain a balance in organizing activities focused on innovative development; to enhance social and economic efficiency; to continuously accelerate the pace of development through expanded reproduction, the goal of which is to provide the population with high-quality food products and ensure the country’s food security without harming the environment
Yarmolenko Y. O.	economic entities must continuously and dynamically maintain a rational balance between the factors of reproduction and the necessary pace of its development in conditions of uncertainty and volatility of the external environment, with the aim of consistently meeting the population’s needs for food and consumer goods produced from agricultural raw materials, both now and in the future, while taking into account the responsibility for creating the necessary social conditions and preventing environmental pollution
Tchaikovsky I. A.	of the agricultural sector and its management entities to create rational production structures that, by mobilizing internal reserves, will help mitigate negative consequences and minimize deviations from established development trends in the event of unforeseen external influences
<i>Ensuring dynamic equilibrium</i>	
Sirotyuk G. V.	Achieving a balance in the functioning of agricultural enterprises, i.e., ensuring the stabilization of their agricultural production and income generation, which can sufficiently support their process of expanded reproduction. The main criterion for such a balance is achieving stable growth in agricultural production and resolving the issue of food security
Ignatenko V. V.	maintaining dynamic equilibrium under real conditions of internal and external changes, sustaining a long-term reproductive process, optimizing environmental parameters, ensuring long-term security in fulfilling specific food supply functions, and raising the social standard of living of the rural population
Popova O. L.	systemic, human-centered changes—focused on the interests and potential of individuals, society, and the —that are adaptive in nature and qualitative in essence, accompanied by increased ecological and economic efficiency, socio-economic progressiveness, and environmental sustainability relative to previous invariant states, as well as in terms of achieving rational models of sustainability at various stages of evolutionary development
<i>Process</i>	
O. G. Korytny	the process of transitioning to a new level of operational efficiency in this sphere under conditions of forming an effective system of state regulation... from the perspective of economic entities, it is characterized by the ability to maintain effective links between factors of reproduction and growth rates under conditions of uncertainty in both the current and future periods, taking into account socio-ecological components
	an organized process focused on the efficient use and reproduction of social, environmental, and economic resources within agricultural production, processing, marketing, and consumption systems, supported by state policies and oriented toward long-term sustainability.
Chaikovskiy I. A.	The process of optimizing the level of agricultural production, preserving and restoring the quality parameters of the agricultural environment, and improving the social status of the rural population while strengthening the country’s food and environmental security.
<i>Development</i>	
Yarmolenko Y. O.	Self-sustaining development of enterprises in the sector with stable growth rates, ensuring the satisfaction of the population’s food needs, strengthening the country’s export potential, and creating favorable living conditions for future generations
Pankov O. I.	such development of human activity that incorporates a balanced consideration of economic, social, and environmental aspects and takes into account the interests of future generations
Kopelets O. O.	the selection of a development path from among a range of alternatives that satisfies the population’s current needs for agricultural raw materials without compromising the ability to meet these needs in the future
Food and Agriculture Organization of the United Nations	rural development that is carried out through the use and protection of natural resources and the implementation of technological and institutional changes that enable the needs of present and future generations to be met

Sustainability, in the broadest sense, refers to the ability to maintain a particular process or state over an indefinite period of time. It is a condition or state that can be sustained over the long term without depleting resources or causing harm to the environment, the economy, or society.

Therefore, summarizing the above, we propose to consider “sustainability of the agricultural sector” as a systemic property of the agricultural sector, viewed as a goal or desired state where a balance of environmental, economic, and social dimensions is achieved and maintained. This, in particular, involves setting specific goals or standards that must be met to ensure that agricultural activities do not deplete resources or harm the environment.

In the agricultural sector, sustainability emphasizes the ongoing ability of agricultural systems to function effectively and produce food without degrading the natural resources or ecosystem services on which they depend.

We believe that the concept of sustainable development, unlike the concept of “sustainability of the agricultural sector,” goes beyond the static functioning of the agricultural system, emphasizing a proactive approach to development that balances the parameters of economic growth, social inclusion, and environmental protection. Given this, when characterizing this concept, it is advisable to rely on a process-oriented approach that addresses environmental, economic, and social dimensions simultaneously [28; 29; 30; 31; 32; 33].

Sustainable development is a process and the strategies used to achieve sustainable development goals. It encompasses a broader range of objectives, including economic and social development alongside environmental protection. Sustainable development involves the implementation of policies, practices, and technologies that promote growth and development in a way that does not harm future resources or the environment, that is, that contributes to the sustainability of the agricultural sector. It also includes addressing issues such as rural poverty, food security, and adaptation to climate change.

Thus, sustainable development aims to create an agricultural system that supports current and future needs, not only ensuring the long-term viability of agricultural production but also enhancing economic stability, improving social conditions, and protecting the environment (Fig. 5).

One of the main goals of sustainable development in the agricultural sector is to minimize environmental impact while increasing production efficiency.

This involves implementing practices that promote responsible management of natural resources—including soil, energy, and water conservation and waste minimization—and biodiversity, ensuring that environmental degradation is minimized and the impacts of climate change are mitigated. A key component of sustainable development in the agricultural sector is economic sustainability, which must ensure sufficient economic returns to support agricultural businesses and provide adequate compensation for producers.

Social sustainability emphasizes fair treatment, inclusivity, and ensuring the equitable distribution of resources among all stakeholders, including farmers and rural communities. Sustainable agricultural production should create opportunities to raise living standards, increase per capita income, and address issues such as poverty and unemployment.

Gender-sensitive agricultural policy promotes social justice by addressing the unique challenges faced by women in agriculture [31]. Encouraging community participation and shared decision-making in agricultural practices enhances social justice [32].

In order to deepen our understanding of the theoretical foundations for ensuring the sustainable development of the agricultural sector, we consider it appropriate to examine the evolution and consolidation of scientific research in this field using VOSviewer, a software tool for constructing and visualizing bibliometric network connections.

In the first stage, we will search for articles on this topic using the SCOPUS scientometric database, which more thoroughly indexes applied scientific journals in the field of business and economic research (compared to WoS).

The following key parameters were selected for the analysis: publication time period: 2000–2024; publication type: article; language of articles - English; combination of keywords used for the search: “sustainable development” AND “agriculture” OR “farming” OR “agricultural sector” OR “agricultural practices”; subject-based restrictions - “business, management, and accounting” and “economics, econometrics, and finance.”

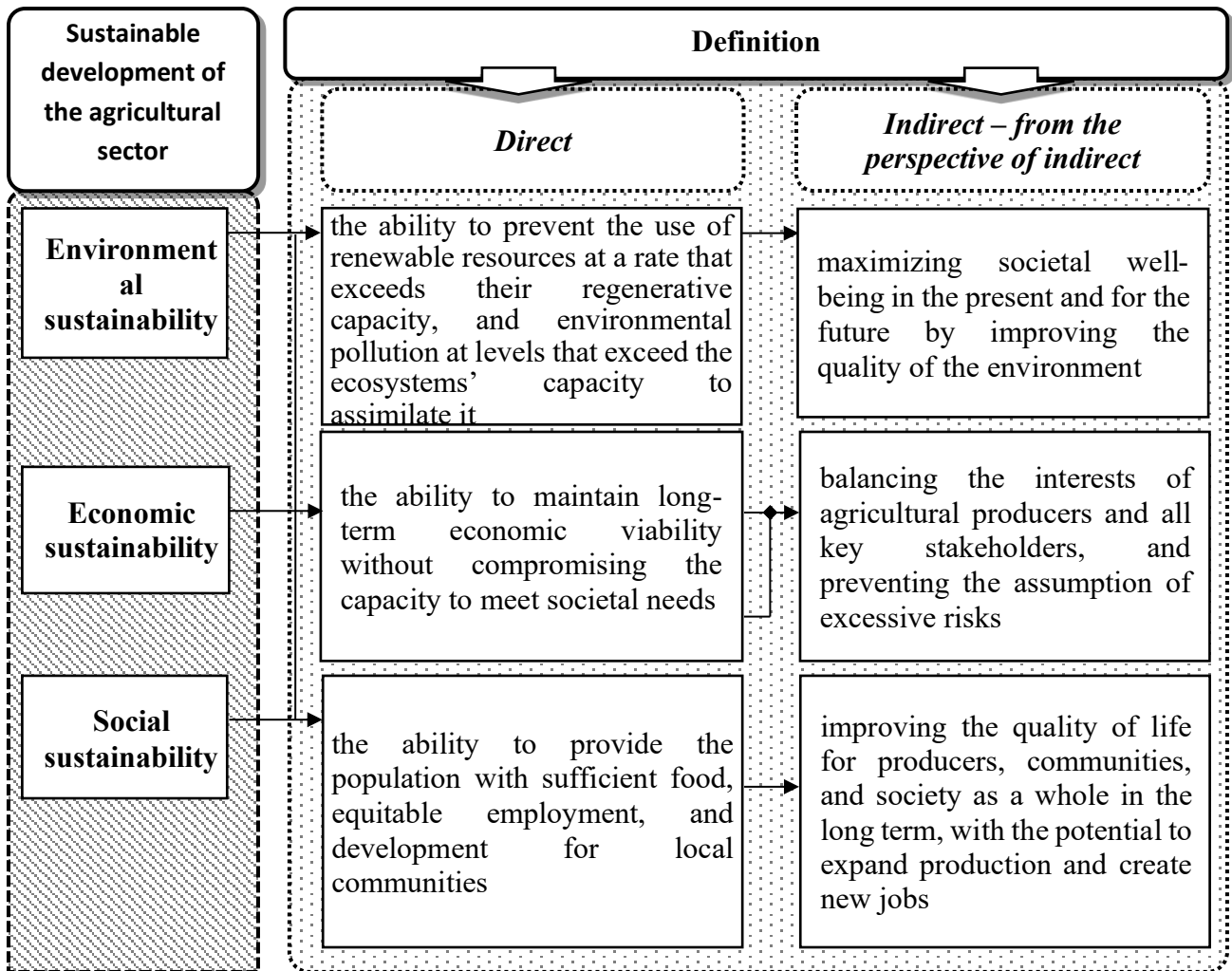
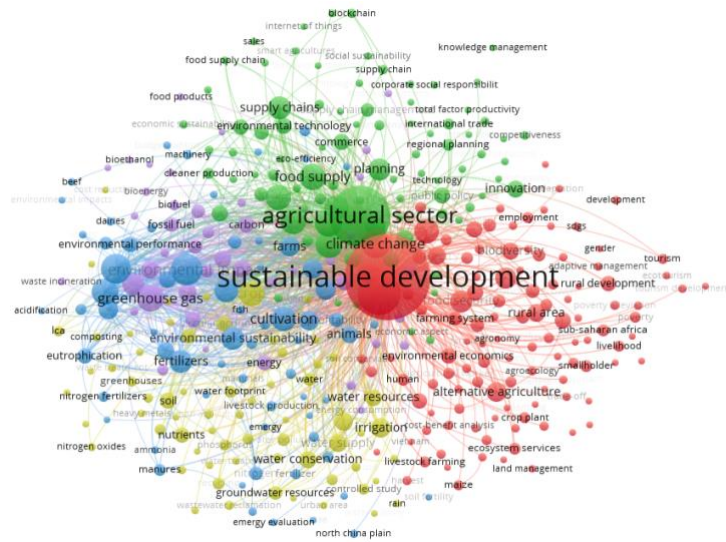


Figure 5. Breakdown of the triadic understanding of the concept of “sustainable development of the agricultural sector”

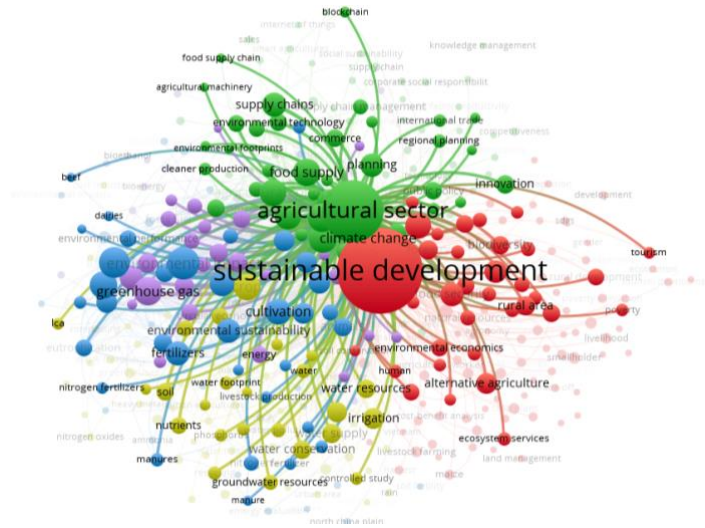
Source: compiled by the author

Based on the results, the following search query was formulated: ((TITLE-ABS-KEY("sustainable development") AND TITLE-ABS-KEY("agriculture" OR "farming" OR "agricultural sector" OR "agricultural practices")) AND PUBYEAR > 2000 AND PUBYEAR < 2024 AND (LIMIT-TO (SUBJAREA, “BUSI”) OR LIMIT-TO (SUBJAREA, “ECON”)) AND (LIMIT-TO (DOCTYPE, “ar”)). As a result, a database of 2,146 articles was created, containing authors’ names, cited publications, journal titles, sponsoring organizations, publication date, country of publication, and keywords, which was subsequently exported to an Excel spreadsheet for further analysis and systematization.

In the second stage, a bibliometric analysis of the generated database was conducted using the VOSviewer tool. Unlike a traditional literature review, this approach eliminates the factor of subjectivity, assesses the significance of scientific work based on the number of citations, and more effectively identifies and analyzes the interrelationships between studies using the “co-occurrence” approach, highlighting related words in the full texts of publications, abstracts, and titles. This made it possible to identify trends in research on the sustainable development of the agricultural sector, uncover key connections between concepts, and determine directions for future research (Fig. 6).



1a) complete thematic map



1b) Fragment of the interrelationships between the concept of the agricultural sector and other concepts

Figure 6. Concept map of the relationships between concepts within the framework of the “sustainable development of the agricultural sector” concept and other concepts for 2000-2024.

Source: constructed using the VOSviewer tool, method: Keyword: Co-occurrence

The central element of the diagram is the concept of “sustainable development,” which is the largest node, around which other keywords are arranged. The high number of connections (379) and the total connection density (11,272) indicate that the objects in the analyzed dataset are closely interconnected with each other and with this concept.

Semantic relationships form five clusters, provisionally labeled as “Sustainable Development of the Agricultural Sector” (red), “Technological Innovations and Management” (green), “Environmental Sustainability” (blue), “Integrated Water Resources Management and Pollution Control” (olive), and “Sustainable Energy Management” (purple). The interpretation of the clusters is based on the thematic focus of the keywords contained within them; however, it should be noted that this division is rather arbitrary, since, as the study results show, both the clusters and the concepts are interrelated. In the identified clusters, the size of an object reflects its total link strength, and the width of the lines reflects the link strength between two terms.

The largest cluster, “Sustainable Agricultural Sector,” includes 113 key concepts and focuses on the implementation of sustainable practices in the agricultural sector that ensure economic development and environmental sustainability. A distinctive feature of this cluster is the integration of sustainable resource management methods, such as climate change adaptation, soil conservation, and efficient use of water resources. Research within this cluster also addresses issues related to the development of agroecology, biodiversity, agroforestry, and the implementation of cutting-edge technologies—such as biotechnology, remote sensing, and geographic information systems—to enhance agricultural productivity.

Research in this cluster covers a wide range of economic aspects related to the sustainable development of the agricultural sector. They aim to improve efficiency, reduce environmental costs, support economic growth based on the analysis of economic processes and models in the agricultural sector, intensify the use of resources, and implement best management practices, including planning, production organization, human resource management, and financial management.

This cluster also includes research on the social aspects of sustainability, particularly the study of agricultural workers’ working conditions, the impact of agricultural practices on local communities, ensuring food security, and the development of local self-governance.

This research cluster aims to provide a multidimensional understanding of sustainable development in the agricultural sector. By combining practices, policy, and environmental considerations, the research is aimed at creating sustainable agricultural systems capable of adapting to climate change, conserving natural resources, and supporting the livelihoods of rural communities.

The second-largest cluster, “Technological Innovation and Management,” containing 89 keywords, brings together a significant number of studies focused on the implementation of advanced technologies and innovations in the agricultural sector, as well as on the management of these processes. The economic context of the research addresses issues of increasing productivity, competitiveness, and efficiency through the integration of artificial intelligence, machine learning, the Internet of Things, blockchain, and digitalization into agricultural practices.

The third cluster, “Environmental Sustainability,” which includes 66 terms, covers research aimed at ensuring environmental sustainability and increasing productivity in the agricultural sector. Research in this cluster focuses on analyzing and reducing the environmental impact of agricultural practices, including studies on measuring and reducing environmental footprints such as greenhouse gas emissions, acidity, and eutrophication. Significant attention is also given to ensuring efficient resource use and increasing agricultural productivity. This cluster explores the interconnections in the study of environmental and socio-economic aspects of sustainability analysis and assessment, including the analysis of costs associated with reducing environmental impacts and the implementation of effective resource management methods to mitigate negative consequences, product life cycle assessment, environmental performance, and scenario analysis. An important aspect is the development of sustainability indicators that allow for the assessment of economic efficiency and environmental performance.

The fourth cluster, “Integrated Water Resources Management and Pollution Control,” comprising 66 terms, focuses on comprehensive water resources management, pollution control, and sustainable water use practices. The main research topics in this cluster include the efficient use of water resources, reducing water pollution, and promoting the sustainable management of water and soil resources.

The fifth cluster, “Sustainable Energy Management,” containing 43 keywords, encompasses a large group of studies dedicated to: the development and optimization of renewable energy sources, such as bioenergy, biofuels, biogas, and biomass, to reduce dependence on fossil fuels and lower greenhouse gas emissions; strategies for reducing carbon emissions and implementing emission control technologies that help mitigate climate impacts and support environmental sustainability. This cluster also explores the economic aspects of effective energy resource management and optimization of their use, including multi-objective optimization, linear programming, and uncertainty analysis to improve the efficiency of decision-making processes in the agricultural sector.

A distinctive feature of this cluster is a comprehensive approach to managing energy resources and production processes in the agricultural sector, ensuring long-term sustainability and economic efficiency.

Thus, based on the conducted research, it can be concluded that comprehensive studies of the sustainable development of the agricultural sector, taking into account the interrelationships and interactions with economic, environmental, and social aspects, predominate. At the same time, research on the sustainable development of the agricultural sector closely intersects with topics such as the management of all types of

sustainability metrics, enabling a more accurate evaluation of the impact of agricultural practices on the environment and socio-economic parameters.

These stages of development demonstrate the formation of a comprehensive approach to the functioning of the agricultural sector, encompassing economic, environmental, and social aspects. The adoption of cutting-edge technologies, such as artificial intelligence and the Internet of Things, contributes to process optimization and greater precision in resource management. In addition, the development of bioeconomy and circular economy concepts opens up new opportunities for the sustainable use of resources and waste minimization.

Thus, current research in the agricultural sector focuses on creating systems that not only ensure high productivity but are also environmentally and socially sustainable. This comprehensive approach allows for more effective solutions to challenges related to climate change, food security, and socio-economic development, thereby providing the foundation for a sustainable future of the agricultural sector (Fig. 8).

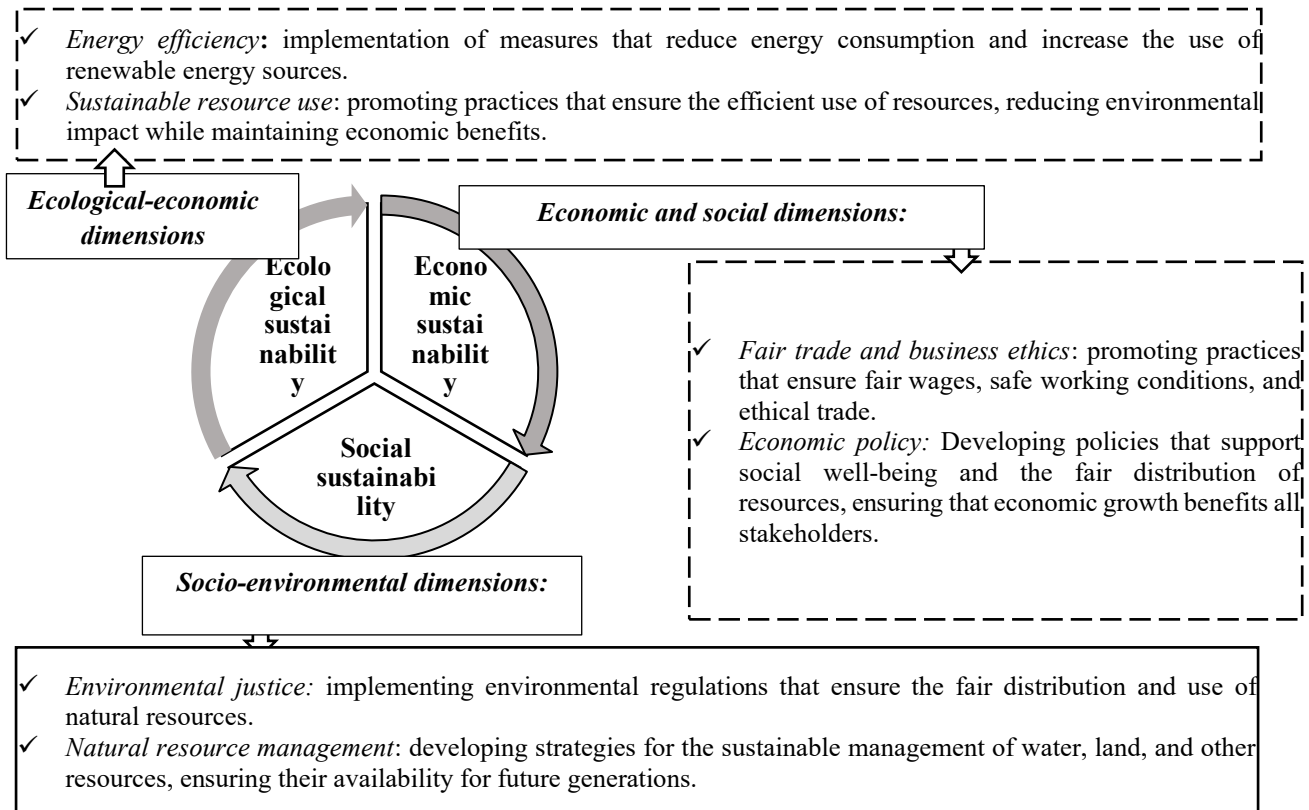


Figure 8. Comprehensive approaches to research on sustainable development in the agricultural sector: integrating social, environmental, and economic dimensions

Source: compiled by the author

Thus, sustainability and sustainable development are interrelated concepts. Sustainable development provides the strategies, mechanisms, and tools necessary to achieve sustainability in the agricultural sector. At the same time, sustainability is a static concept focused on maintaining a state of equilibrium, while sustainable development is a dynamic process emphasizing continuous improvement and adaptation. Given this, we propose to view sustainability as a goal or state that must be achieved, while sustainable development is the process and strategies for achieving this goal. It should be emphasized that the dimensions of sustainability in the agricultural sector cannot be maximized simultaneously, as they are largely mutually exclusive. Therefore, when developing mechanisms to ensure the sustainable development of the agricultural sector—primarily at the state level—it is necessary to define specific targets that will optimize the relationships and interdependencies among these dimensions, thereby enabling the development of a balanced approach. Thus, achieving sustainable development in the agricultural sector requires coordinated efforts to address the complex interplay of environmental, economic, and social factors. By applying holistic approaches that combine environmental principles with socio-economic considerations, it is possible to achieve sustainable agriculture, ensuring food security, overcoming poverty, and protecting the environment.

In the coming decades, the agricultural sector will undergo significant changes: agricultural systems must reduce their environmental impact while producing enough food for a growing population, amid the negative effects of uncertainties and threats of various origins (climatic, economic, social, political) [34]. Given this, agricultural systems must adapt or transform to remain sustainable.

Sustainable development is a comprehensive framework that shapes changes in the agricultural sector. This concept not only helps address current challenges but also fosters a resilient and sustainable agricultural sector capable of achieving its operational goals amid future uncertainties and threats.

Within the scope of this study, we consider it appropriate to examine the model of sustainable development based on the postulates of the systems approach, which views development as “an irreversible, directed, and regular change in the state of a system (object) based on objective laws. As is known, the nature and pace of this process determine whether such changes are evolutionary or revolutionary. The result of development is a new quality of the system” [35].

Therefore, we consider it appropriate to view the sustainable development of the agricultural sector as a complex and multifaceted process encompassing a wide range of shifts, ranging from gradual evolutionary adjustments to transformations caused by factors and triggers of external and internal origin, which lead to changes in its structure, organization, functioning, and role in the economy, and are aimed at ensuring long-term ecological balance, social justice, and economic viability.

To develop a model of sustainable development for the agricultural sector, we consider it appropriate to take into account the tenets of the theories presented in Table 3.

Table 3. Characteristics of theories relevant for developing a model of sustainable development of the agricultural sector [compiled by the author based on 36; 37; 38; 39; 40; 41; 42; 43]

Theory	Main focus	Key advantages	Application in the agricultural sector
<i>Basic concepts</i>			
systems	the study of a specific object as a holistic set of components within a network of relationships and connections between them, i.e., viewing the object as a system model	the ability to analyze complex nonlinear interactions, feedback mechanisms, and dependencies, taking into account the interaction of system components and their capacity for self-organization, as well as the emergence of emergent phenomena and systemic effects	the development of conceptual foundations and the justification of theoretical-methodological, methodological principles, and practical recommendations for improving the process of systemic transformation of the agricultural sector of the economy
institutional	role of institutions in shaping organizational behavior and change, including analysis of legislation and policy.	opportunity to gain a deeper understanding of how institutions, historical context, and socio-cultural factors shape economic processes and outcomes	the opportunity to identify the influence of political and economic structures, both formal and informal, on transformations in the agricultural sector
synergistic	the study of self-organization processes and the emergence of new structures in conditions of instability or crisis situations	the ability to analyze economic processes as nonlinear and capable of self-organization, i.e., the creation of new orders and structures under the influence of internal and external factors	the ability to assess the interrelationships between factors affecting the agricultural sector; to identify development scenarios for the agricultural sector under various conditions and to study potential bifurcations
resilience	focus on the ability of systems to absorb disturbances and reorganize during changes in order to preserve core functions and structures	improving the adaptive mechanisms of economic systems	ensuring adaptation to climate change, market fluctuations, and other shocks through the implementation of appropriate mechanisms, tools, and self-organization

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<i>Dynamic aspects</i>			
Evolutionary	studying gradual changes and adaptive processes in systems	the ability to analyze economic processes as open and irreversible systems that are constantly influenced by and respond to external and internal environments; the conclusion that periodic and appropriately selected actions on the system can reduce the likelihood of collapse	identification of interrelationships with external and internal factors, realistic forecasts regarding long-term development, on the basis of which informed management decisions can be made; development of comprehensive development strategies to prevent the degradation of agricultural systems;
dependence on the path	consideration of the impact of past events on current policy and practice	understanding the constraints on the path to new practices in the technological, institutional, and organizational spheres	a slow transition from traditional to modern sustainable practices due to historical inertia.
<i>Comprehensive consideration of technical, social, and environmental innovation factors</i>			
diffusion of innovation	research into how and why new ideas and technologies spread in societies	the ability to identify factors influencing the rate of innovation adoption in the agricultural sector	the ability to analyze the integration of innovations into the overall system of agricultural production technologies
environmental modernization	examining economic growth from an environmental perspective	Support for innovative solutions to environmental challenges	taking environmental productivity into account (the productive use of natural resources and environments) can be a source of further growth and development
socio-technical systems	considering the interrelationship between social and technical aspects, emphasizing the importance of synergy between them	A comprehensive approach to change based on the interaction between social (people, organizational structures, culture) and technical (technologies, equipment, processes) components	integration of new technologies while taking into account social factors and barriers, including access to knowledge, policy support, and changing social values.

Within the framework of our study, we consider the systemic and institutional approaches to be fundamental, primarily because the essence and components of the agricultural sector are formalized on their basis. In the context of studying the sustainable development of the agricultural sector, the systemic approach allows for the analysis of complex nonlinear networks of interactions and feedback channels, taking into account the interdependencies of system components, their capacity for self-organization, and the emergence of emergent phenomena and systemic effects.

The systemic approach is complemented by the institutional approach, as the latter examines the role of formal and informal institutions, norms, rules, and traditions in the sustainable development of the agricultural sector.

In doing so, it is necessary to account for the complex interactions between various institutions, including international organizations, the government, and non-governmental institutions, which both influence the development trajectory of the agricultural sector and are themselves transformed by its influence.

An important characteristic of the institutional approach is that, in the process of studying sustainable development in the agricultural sector, it allows for consideration of the role of stakeholder interest groups, specifically how they can lobby for changes in the agricultural sector and how their influence shapes the regulatory and normative environment.

The institutional approach also has dynamic characteristics, as it recognizes that changes often occur gradually over long periods of time, while the cumulative effects of previous institutional frameworks influence the current state of the agricultural sector.

The synergistic approach emphasizes processes of self-organization and the emergence of new structures in conditions of instability or crisis situations. Its application to develop a model of sustainable development for the agricultural sector identifies and formalizes the stages of its adaptive and transformational development, distinguishing phases of imbalance, bifurcation, degradation, and collapse; It accounts for the multiplicity and alternative paths of the agricultural sector's development at bifurcation points, when processes become chaotic and a transition to a new attractor occurs.

In addition, identifying bifurcation points allows us to understand when and how the agricultural sector may change under the influence of internal and/or external factors.

Resilience theory posits that a high level of resilience enables the agricultural system to remain in its current state. At the same time, it should be noted that a high level of resilience may, in certain cases, prevent the achievement of sustainable development goals (for example, global dependence on fossil fuels has a high level of resilience, and if societal goals involve reducing this dependence, the high resilience of the energy system may hinder changes in the desired direction).

Since we are studying the sustainable development of the agricultural sector as a dynamic phenomenon, it is advisable to take into account the postulates of the evolutionary approach and the path-dependence approach, which allow for the study of gradual changes and adaptive processes in the agricultural system while also accounting for a certain inertia in these changes.

The evolutionary approach, in this context, ensures contextual sensitivity, as it establishes that the model of sustainable development of the agricultural sector exhibits significant differences across various regions and countries due to their unique characteristics, which determine evolutionary determinism.

By incorporating theories of innovation diffusion, ecological modernization, and socio-technical systems, it is possible to develop a model of sustainable development for the agricultural sector that accounts for the complex interactions and mutual influences of social, technical, economic, and environmental factors. Applying these theories helps not only to understand current challenges but also to develop strategic solutions for overcoming future challenges and leveraging opportunities to ensure the sustainable development of the agricultural sector.

Summarizing the material presented above, we have developed a conceptual approach to a cyclical model of sustainable development in the agricultural sector, presented in Figure 9.

We propose considering the evolutionary and revolutionary stages of sustainable development within the cyclical model, in accordance with the general understanding of the concept of "development" under a systems approach, by distinguishing the corresponding key modes-adaptation and transformation [44; 45; 46].

Theoretical discussions surrounding adaptation and transformation include the question of whether these two processes are part of a single continuum or whether they are distinct [47]. Some researchers believe that adaptation and transformation represent two distinct but interrelated processes. Adaptation can be a way of gradually responding to changes, ensuring resilience, while transformation can serve as a strategic response to significant and radical changes aimed at altering the very essence or direction of the system.

However, there is also an approach that adaptation and transformation can occur gradually and at different levels. For example, adaptation can be the first stage in the transformation process, where the system gradually adjusts to new conditions, after which transformation occurs.

We believe that although adaptation and transformation can be viewed as distinct processes with different goals and outcomes, within the context of the cyclical model of sustainable development, they generally interact and occur in different ways depending on specific conditions and context, and are interrelated.

To develop a cyclical model of sustainable development, we consider it appropriate to clarify the concepts of "adaptation" (Table 4) and "transformation" (Table 5).

The adaptation mode is characterized by gradual changes within a stable context, which may be perceived as such due to various socio-cognitive barriers [48]. Changes within this mode are described as a continuation of "what is already being done" [49], "gradual changes that allow the system to preserve its basic functions and characteristics" [50].

During the adaptation process, agricultural producers preserve their values and norms and may also implement specific strategic changes that remain under their control. This allows them to continue generating income from their activities while preserving their identity [51]. This regime involves the integration of new technologies that optimize resource use, improve existing processes, and, on this basis, reduce environmental impact and increase productivity [52].

Summarizing the above definitions, we have determined that most approaches emphasize the goal of adaptation as reducing the agricultural sector’s vulnerability to climate change (Burton I., Lim B., National Academy of Sciences of the USA, World Bank). While generally agreeing with this, we believe that the adaptation of the agricultural sector should address a broader range of factors and threats generated by the operational environment.

It is important to note that effective adaptation should not only reduce risks but also capitalize on new opportunities (Burton I., Lim B., Ivanyuta S. P., et al.).

Adaptation is generally associated with changes in practices and structures in both natural and human systems, and with the introduction of new methods and technologies to enhance the resilience and efficiency of the agricultural sector (National Academy of Sciences of the United States, World Bank), which can be implemented at the level of individual producers, communities, regions, and states (Intergovernmental Panel on Climate Change, World Bank).

Therefore, summarizing the above, we consider it appropriate to define the adaptation of the agricultural sector in the context of its sustainable development as a comprehensive process of implementing strategic measures and changes in agricultural practices, technologies, resource management, and institutional structures with the aim of reducing vulnerability to current and future changes in key factors affecting it, as well as the use of new opportunities to ensure long-term environmental balance, social justice, and economic viability.

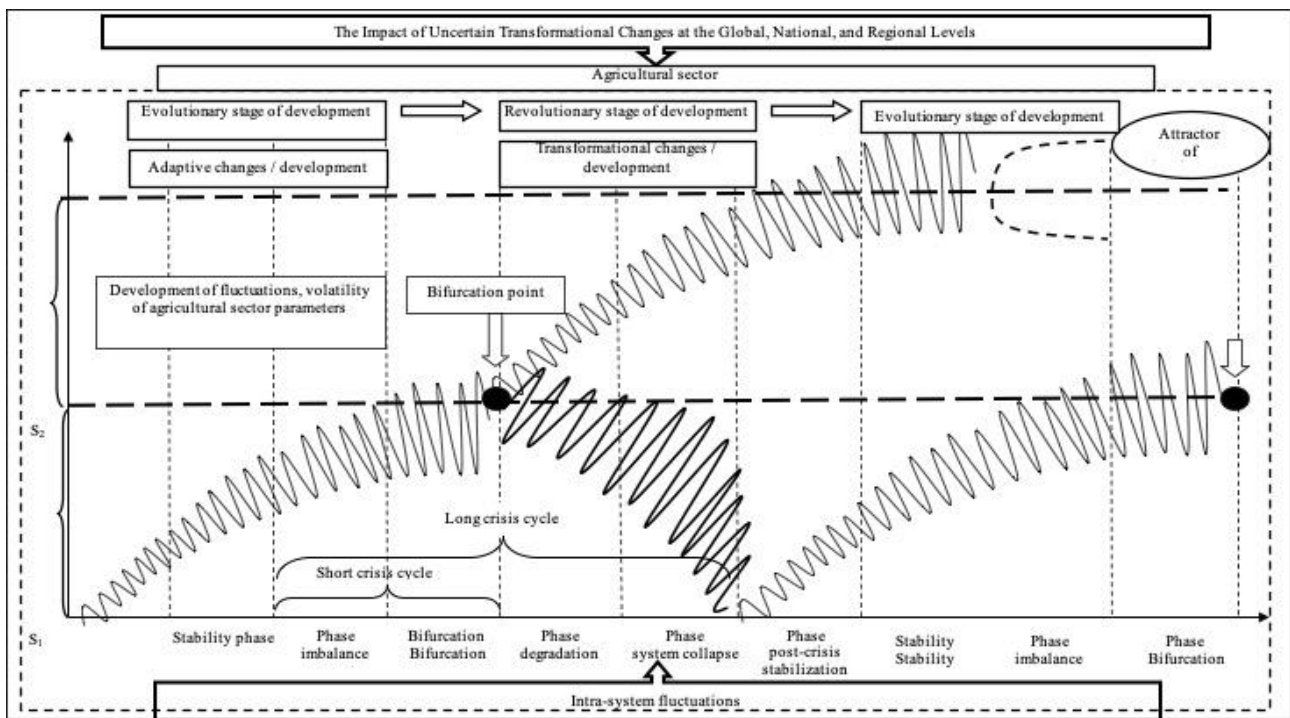


Figure 9. Cyclical model of sustainable development of the agricultural sector
 Source: developed by the author

This process involves both proactive and reactive actions at various spatial levels -from individual farms to national and global scales - and requires coordination among producers, the private sector, and government organizations.

Based on the results of our study, we determined that there is no single established definition of the concept of “transformation” as such, particularly as it pertains to the agricultural sector (Table 5).

By synthesizing the above definitions, several key approaches to understanding the essence of the agricultural sector’s transformation can be identified.

Table 4. Approaches to understanding the concept of “adaptation” in the context of the agricultural sector’s functioning [compiled by the author based on 53-64]

Author / Organization	Definition
Oliiferuk S. I.	The process of changes in the quantitative and qualitative characteristics of a system, allowing it to achieve an optimal or, under critical conditions, a limiting state of functioning in changing conditions. Systems capable of changing their parameters in accordance with external conditions—that is, of adapting—are called adaptive, and the functioning of adaptive systems is based on a feedback mechanism
Onysko S. M.	the process of adjusting their parameters to the uncertain conditions of the environment, ensuring an increase in the efficiency of their functioning throughout their entire life cycle
Ivanyuta S. P. et al.	The process of adaptation in natural or human systems in response to actual or expected climatic influences, which will reduce their negative consequences and take advantage of favorable opportunities.
Ministry of Environmental Protection and Natural Resources	the ability of systems, institutions, people, and other organisms to adapt to potential harm, take advantage of opportunities, or respond to consequences
Schenefeld, J. J., Schulze, K.; Bruch, N.	measures aimed at enhancing the ability of people and communities to adapt to climate change and related impacts that will occur in various sectors of human life
Burton, I.; Lim, B.	actions aimed at reducing vulnerability and/or taking advantage of opportunities arising from current or future climate change
Intergovernmental Panel on Climate Change	the process of adjusting to actual or expected climate changes and their consequences. In human systems, adaptation seeks to mitigate or avoid harm, as well as to take advantage of beneficial opportunities. Furthermore, adaptation measures undertaken by humans can also occur in natural systems, where actions are taken to promote “better” adaptation to a changing climate
World Bank	the process of introducing new methods and strategies in agriculture aimed at reducing risks associated with climate change, increasing resilience, and ensuring food security
European Environment Agency	changes in agricultural practices, water management, crop selection, and land-use planning aimed at reducing the negative impacts of climate change on agriculture
National Academy of Sciences	a set of actions aimed at reducing agriculture’s vulnerability to climate change through the adoption of new technologies, changes in farming practices, and the development of policy strategies
Food and Agriculture Organization of the United Nations	changes in practices, processes, and structures that enable agriculture to adapt to climate change, thereby reducing vulnerability and capitalizing on new opportunities

Table 5. Approaches to understanding the concept of “transformation” in the context of the agricultural sector’s functioning [compiled by the author based on 59, 65-73]

Author / Organization	Definition
Hrazhevskya N. I.	In a broad sense: a form of economic system development associated with evolutionary (a gradual process of changes in system parameters) and revolutionary changes (the moment of the system’s transition to a different development trajectory), as well as transitions of economic systems from a stable to an unstable state. In a narrow sense: a component of the evolutionary process, as a process of system renewal during abrupt qualitative transformations
Malik M. Y.	A method for resolving contradictions between market demands and the outdated logic of economic agents’ behavior, consisting of organizational, economic, financial, legal, and technical measures aimed at reorganizing enterprises, changing forms of ownership, management, and organizational-legal forms, which will contribute to the financial recovery of the economy, an increase in the output of competitive products, and improved production efficiency
Marushchynets A. V.	The process of changing the institutional, sectoral, and territorial nature of the region’s agricultural sector, driven by the transformation of the entire economic system. From the perspective of human geography, when examining transformational processes in the region’s agricultural sector, key attention should be paid specifically to their territorial aspect

Kartashova O. G., Barsuk Y. V.	A qualitative transformation of a specific model or state, or any sector, into a new order required by the internal and international market conditions of the agricultural sector during a specific period (mobilization and modernization)
Negoda Y. V.	A natural-evolutionary process of social development aimed at enhancing the sustainability of economic growth through the expanded reproduction of all types of resources and the qualitative transformation of the population's standard of living, based on profound, large-scale changes in the socio-economic structure of the agro-economy, various forms of economic activity and methods of agricultural production, and the institutional market environment
	A multi-variant process of development of its elements: economic agents, formal and informal institutions, economic order, and processes, leading to a fundamental transformation of the entire economic system
Vermeulen, S. J., et al.	A set of structural changes in national economies, resulting in the agricultural sector's share of GDP and employment declining, but its productivity increasing
Center for International Agriculture	The adoption of innovative technologies, changes in agricultural and land-use systems, and improvements in farming practices to increase productivity, sustainability, and economic efficiency, while reducing negative environmental impacts
Asian Development Bank	A process of profound and systemic change that includes reforming institutional structures, modernizing technologies, and introducing innovative practices to enhance the productivity, sustainability, and economic viability of agricultural systems
European Commission	Comprehensive changes in policy, technology, and governance aimed at creating more sustainable, competitive, and environmentally responsible agricultural systems capable of adapting to global challenges such as climate change and demographic shifts
UN Food and Agriculture Organization	Changing the ways agricultural products are produced, managed, and distributed to enhance food security, climate resilience, and economic growth through the adoption of sustainable and innovative practices

Malik M. Y., the Asian Development Bank, and the European Commission emphasize the importance of organizational and managerial, financial and economic, legal, and technical measures for transformation. This includes, in particular, the reorganization of enterprises, changes in ownership structures, the modernization of technologies, and the reform of institutional structures.

Marushynets A. V. and others emphasize the territorial and institutional aspects of transformation, highlighting the importance of changes in the institutional, sectoral, and territorial structures of the agricultural sector. This is crucial for understanding local characteristics and the specifics of regional development.

Kartashova O. G., Barsuk Y. V., and the Center for International Agriculture emphasize qualitative transformations and the adoption of innovative technologies. This includes the mobilization and modernization of the agricultural sector, as well as improvements in productivity, resilience, and economic efficiency.

Vermeulen S. J., the UN Food and Agriculture Organization, and the European Commission view transformation as a set of structural changes aimed at creating sustainable, competitive, and environmentally responsible agricultural systems. This involves a shift from traditional methods to innovative and productive practices that enhance efficiency and reduce negative environmental impacts.

Transformation begins with the recognition of the need for more radical changes, which may be triggered by "trigger events" such as economic, climatic, or environmental problems exacerbated by the instability of the operational environment (external or internal to the agricultural sector) [74-76].

Unlike adaptive changes, transformational changes are defined as those that: "1) are implemented on a much larger scale or with greater intensity; 2) are truly new to a specific region or resource system; 3) transform places and alter their configuration" [49]; are more abrupt and involve the system's transition to a new state [77]. According to the approach of O'Brien K. and Hochačka G., transformational changes include not only radical technical changes but also changes in "meaning-making" (i.e., changes in the intentions and attitudes underlying behavior) [78]. This approach is close to the concept of "significant change" proposed by Sutherland L.-A. and others in [74], using the example of the transition to organic farming, which is also considered a transformational change.

Transformational change involves "the reorientation of a significant number of agricultural activities or resources, for example, through a shift from commercial agriculture to social farming or other diversification activities," unlike adaptive change, which is merely "a change in agricultural activity that does not alter the direction or focus of the farming system" [44].

Vermeulen S. J. et al. [70] defined transformational change in the agricultural sector according to the following criteria: a response to climate risks, usually in combination with other factors (quality); redistribution of at least one-third of primary factors of production (land, labor, capital) and/or products and production outcomes (types and volumes of production and consumption of goods and services arising in multifunctional agricultural systems) (distribution); over a 25-year period (duration).

The transformation phase differs from the adaptation phase in its intensity and depth of impact on agricultural practices and technologies. Key aspects of this phase include the adoption of innovative technologies and practices, structural changes in agricultural production, integrated supply chain management, the development of new markets, and economic transformations.

The transformation phase is critical for ensuring sustainable development, as it involves fundamental changes that enhance the efficiency and resilience of the agricultural sector and reduce its environmental impact.

Given the current conditions, characterized by a growing number of threats and challenges to the sustainable development of the agricultural sector, adaptation alone will be insufficient: transformational changes are necessary [49; 74]. For example, gradual adaptive adjustments may allow for better management of climate risks and opportunities in the short term [44; 79], but more radical changes will be necessary to ensure the long-term viability of the agricultural sector [80]. For instance, reducing greenhouse gas emissions to achieve sustainable development goals requires precisely such transformational changes [77; 80]. Furthermore, incremental adaptive measures carry the risk of decisions that lock agricultural systems into suboptimal development trajectories, failing to ensure the achievement of sustainable development goals.

Thus, based on a synthesis of scholarly approaches, the transformation of the agricultural sector can be defined as a comprehensive process of profound structural changes, encompassing the transformation of organizational, institutional, technological, and territorial aspects of the agricultural sphere. This process aims to increase the productivity, resilience, and economic efficiency of agricultural systems through the introduction of innovative technologies, the modernization of production methods, adaptation to global challenges, and the assurance of food security and environmental responsibility.

Table 6 presents a summary of the characteristics of adaptation and transformation within the framework of sustainable development of the agricultural sector.

To provide a detailed and in-depth analysis of the stages of sustainable development in the agricultural sector, based on the principles of a synergistic approach, we consider it appropriate to identify the phases of imbalance, bifurcation, degradation, and collapse, as it is precisely to prevent their occurrence that appropriate mechanisms and tools must be developed.

Due to the influence of external factors, such as climate change, economic crises, or social conflicts, and/or internal changes, the agricultural sector, as an open system, may deviate from a state of equilibrium and transition into a phase of destabilization.

Identifying and assessing these factors is crucial for developing and implementing strategies to support a resilient and adaptable agricultural sector in the face of potential changes and crises. It is undeniable that the issue of the agricultural sector's vulnerability and sustainability is becoming increasingly significant and timely [81], particularly regarding natural disasters exacerbated by climate change and social conflicts.

Within the scope of this study, we propose to consider the factors determining changes in agricultural systems using a systemic and synergistic approach, and to include in their composition the internal factors of the agricultural sector's components as a system, their properties, and their interrelationships within a single complex, which depend on environmental conditions and are determined by the level of bifurcation changes based on the fluctuation component.

Destructive coherent potential is determined both by objective aspects related to the influence of uncontrollable external environmental factors and by subjective factors determined by the internal characteristics of the agricultural sector's components, in particular, the efficiency of operational and management systems and processes, and the adequacy of institutions.

Table 6. Characteristics of adaptation and transformation in the context of sustainable development of the agricultural sector [summarized by the author]

Characteristic	Adaptation	Transformation
Purpose	Reducing vulnerability to current and future changes, leveraging new opportunities, and ensuring the resilience of agricultural systems. It is a response to external changes and involves gradual adjustments	Profound and fundamental changes in the socio-economic structure, organization, and management of the agricultural sector, aimed at restructuring the system in accordance with new market and social conditions
Intent and purpose	Spontaneous as a reaction to immediate challenges, or planned, with long-term strategies to prepare for possible changes	The need for strategic planning, the necessity of significant changes in the structure and functioning of agricultural systems
Initiative	Private (autonomous), implemented by individuals in their own interests; public, implemented by government entities and aimed at the common good (public goods or actions to correct market failures)	
Intensity	Improvement of existing systems and processes	Qualitative renewal of the system
Timing and duration	Proactive, simultaneous, or reactive adaptation	Proactive, simultaneous, or reactive transformation with a focus on long-term impact
Scale	From the local level (field, farm) to the regional or national level, with an emphasis on practical changes in agricultural practices.	Covers broader scales: regional, national, and global levels with an emphasis on structural and institutional transformations
Responsibility	Individual farmers, private enterprises, government agencies.	Coordination of actions by governments, the private sector, and farming communities.
Form	Administrative, financial, institutional, legal, managerial, and technological measures.	Comprehensive solutions that include policy reform, the introduction of new institutional structures, business models, etc.
Constraints and challenges	Financial resources, government support, social barriers.	Lack of coordination, resistance to change, economic and social challenges.

A summary of external influencing factors that may necessitate its adaptation/transformation to ensure sustainable development is presented in Table 7.

Table 7. Classification of external factors influencing the adaptation/transformation of the agricultural sector to ensure sustainable development [compiled by the author based on 53; 82-94]

Level Factor	Global	National	Local
	Differentiation based on the level of impact and characteristics of the territory where the agricultural producer is located, as well as the specific conditions of the country		
Ecological and climatic	Climate change, including changes/variations in temperature, precipitation, evapotranspiration, water balance, and hazardous natural phenomena (heavy rains, droughts, floods, etc.). Level of climate variability.		
	Global depletion of natural resources and environmental pollution	Level of air and water pollution Changes in biodiversity and soil quality	The state of local ecosystems
Political	Global political uncertainty Global political conflicts. Sanctions. Geopolitical conflicts, shocks, and uncertainty Global political initiatives on sustainable development and climate change	Domestic political instability Ineffectiveness of the regulatory environment Ineffectiveness/ lack of government support for the agricultural sector High levels of corruption Military actions by other countries	Ineffectiveness of local government and politics Inefficiency/ Lack of local support for the agricultural sector

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Economic	Global economic dynamics. Uncertainty in global markets. Dynamics of global prices for agricultural products. Convergence and evolution of international regulatory standards. Changes in the nature of resource consumption and their cost	National macroeconomic instability and shocks. Macroeconomic uncertainty. Lack of a clear agricultural policy. Insufficient infrastructure development. Limited access to financing and credit	Insufficient level of economic development in communities. Insufficient infrastructure development
Social	Global demographic changes.	Demographic changes (rural migration, aging population, changes in the labor force structure)	
	Social and cultural changes affecting the requirements for production and products in the agricultural sector (increasing demand for organic products, high-value-added products, etc.)		
	Social instability and conflicts		
	Global pandemics.	Level of public health.	
	Insufficient social support.		
Technological	Global cultural influences	National traditions and cultural influences	Local traditions and cultural influences
	Adoption of global digital technologies	Development of national IT infrastructure. Level of digital inclusion	Accessibility of digital technologies, expansion of IT infrastructure

A combination of external factors can pose significant threats to the sustainable development of the agricultural sector, as their impact on the production, supply, and marketing of agricultural products reduces the sector’s productivity and the standard of living in rural communities, while limiting access to food, particularly for vulnerable groups.

To classify changes in the external environment as transformational, they must meet the following criteria:

- scale: the change affects multiple levels of the agricultural system, from local to global;
- depth: the change in the factor/trigger deeply penetrates the core functions of the agricultural sector, affecting resource characteristics, value creation processes, supply chains, and management structures;
- persistence: the impact has a long-term effect rather than being temporary fluctuations in specific indicators;
- systemic impact: the factor/trigger alters fundamental dynamics and relationships, leading to the emergence of new configurations and practices.

Most transformational changes result from shocks, the exceeding of critical levels in strong trends of key variables, or the falling below threshold values. Understanding and quantifying these transformational changes is a crucial element in developing strategies that not only mitigate their negative impact but also leverage the opportunities they present to ensure the resilience and sustainability of agricultural systems.

An important characteristic of transformational changes in the external environment is their uncertainty, which complicates the processes of managerial decision-making, strategic planning, and the implementation of sustainable practices, thereby affecting the agricultural sector’s ability to achieve sustainable development.

External environmental factors and the types of uncertainty they generate are interrelated, creating a complex operational environment that simultaneously affects the economic, social, and environmental aspects of agricultural production (Fig. 10).

The sustainable development of the agricultural sector is also determined by subjective factors stemming from its internal characteristics, which result from the ability of its participants to create, integrate, and reconfigure resources, adapt/transform value creation processes, and integrate innovations into production processes in accordance with changes in the external environment, that the resulting synergistic effect ensures the efficient production of agricultural products in alignment with social and environmental goals.

One of the key internal aspects of sustainable development is the agricultural sector’s ability to effectively utilize existing resources, as well as to create new ones, integrate them into production processes, and reconfigure them in response to changes in the external environment. This process is defined as an enterprise’s dynamic capabilities, which characterize its capacity for innovation and transformation [95]. The ability to reconfigure resources is particularly important in the context of climate change and environmental requirements, as it enables a rapid transition to sustainable production models.

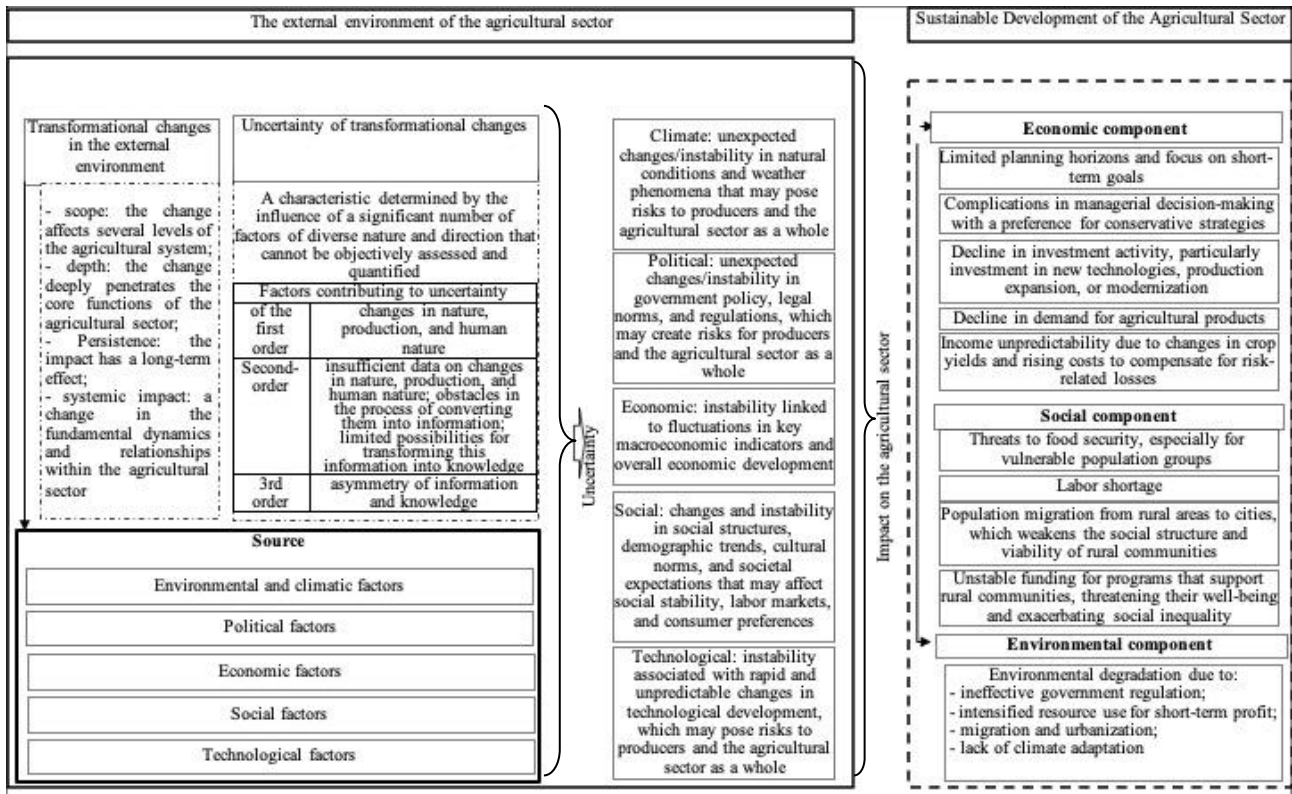


Figure 10. Conceptual approach to determining the impact of uncertain transformational changes on the sustainable development of the agricultural sector
 Source: developed by the author

Sustainable development of the agricultural sector is also determined by the alignment of processes and value chains with its goals and principles. This means that agricultural production through the implementation of appropriate technologies must not only provide economic benefits but also meet social and environmental goals.

According to J. Pretty, “new approaches are needed that will allow for the integration of biological and ecological processes into food production, minimize the use of non-renewable resources that harm the environment or the health of farmers and consumers, and make productive use of farmers’ knowledge and skills” [12].

The integration and reconfiguration of resources, combined with the improvement of value-creation processes, can create a synergistic effect where the overall result exceeds the sum of the individual effects. This can manifest itself in increased productivity, reduced costs, improved product quality, and minimized negative environmental impact. The synergistic effect can also contribute to enhancing the competitiveness of agricultural enterprises in the global market, as they are able to respond more quickly and effectively to changes in the external environment.

Sustainable development of the agricultural sector is based on the concept of a sustainable business model for the agricultural sector, which is intended to “... help develop integrative and competitive solutions that either radically reduce negative impacts or create positive environmental effects for the natural environment and society” [96]. The inability or unwillingness of agricultural producers to adapt or transform business models in light of external factors and internal changes leads to the degradation of agricultural production.

For an in-depth study, we have developed a system of additional indicators that will allow for the analysis of the main characteristics of external and internal factors, presented in Appendix B.

Depending on the accumulated destructive coherent potentials, the complexity and structure of the channels through which threats to the sustainable development of the agricultural sector spread, the scale and direction of external influences, the combination of factors affecting the agricultural sector and the complex of its feedback reactions, the negative consequences of fluctuations can be overcome (return to the stability

phase), keeping the agricultural sector on its current development trajectory, or a transition to the bifurcation point will begin.

We propose understanding the bifurcation point as a critical point of change in its development trajectory, at which the destructive coherent potential increases, leading to destabilization and the intensification of the uncoordinated movement of system elements relative to internal and external fluctuations. It determines the moment from which the formation of possible states of the agricultural sector begins, depending on the decisions made and measures implemented. As noted in [97], “the significance of bifurcation points also lies in the fact that only at these points is it possible to influence the system’s behavioral choices and its future through non-forceful, informational means—that is, through actions of any degree of weakness.” At this point, the agricultural sector is particularly sensitive to external and internal influences, and even minor changes can lead to drastic outcomes. For example, the choice between traditional intensive farming and organic farming can have long-term consequences for environmental sustainability and economic stability [70].

Since the significance of bifurcation points lies in their ability to influence the choice of the agricultural sector’s future development trajectory, identifying them allows us to predict when and how the agricultural sector may change under the influence of internal factors (e.g., innovation, changes in management approaches) or external factors (climate change, market fluctuations). Understanding these issues and the timely implementation of appropriate measures ensure the sustainable development of agricultural systems, reducing their vulnerability and increasing their resilience to changing conditions.

The role of government regulatory bodies is to effectively leverage fluctuations through the implementation of appropriate interventions and, on this basis, ensure the sustainable development of the agricultural sector. Government regulators must take preventive measures to identify and eliminate risks in the agricultural sector to prevent destructive processes within it [94]. Ensuring the sustainability of the agricultural sector in this context involves not only identifying and eliminating vulnerabilities but also creating mechanisms and structures that enable rapid adaptation and recovery in conditions of uncertainty and change.

If the positive scenario is realized, the agricultural sector could transition to a transformational mode that would enhance its sustainability—including resilience to climate change—reduce its negative environmental impact, and improve the socioeconomic conditions of local communities [70].

If the agricultural sector fails to find effective pathways for transformation, it may enter a phase of degradation, where its productivity and resilience decline, which could ultimately lead to its collapse. For example, this could include the continued use of environmentally harmful practices or insufficient adaptation to climate change. This could result in land degradation, a decline in biodiversity, a deterioration of the socioeconomic condition of local communities, and increased vulnerability to climate disasters. In the long term, this could threaten food security and the economic well-being of regions dependent on agricultural production.

Thus, we have formulated the conceptual foundations for ensuring the sustainable development of the agricultural sector based on a model of its cyclical development, which, unlike existing models, allows us to distinguish stages of adaptation and transformation, identifying phases of imbalance, bifurcation, degradation, and collapse; takes into account the influence of uncertainty and the multi-variant, alternative nature of the agricultural sector’s development at bifurcation points. This has formed the scientific basis for developing a scientific and methodological approach to creating tools for assessing and ensuring the sustainable development of the agricultural sector.

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