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INNOVATIVE TRANSFORMATIONS OF THE AGRICULTURAL COMPLEX IN THE CONTEXT OF GLOBAL CHALLENGES OF SUSTAINABLE DEVELOPMENT

Abstract. It is determined that ensuring food security and healthy nutrition for the growing population of the planet will remain a challenge for the world community. The global dominants and tendencies of development of agro-production activity within the global market of agro-food products are analyzed. The grouping of leading countries with a highly innovative agro-industrial sector, which is formed taking into account the goals of sustainable development based on the construction of a clustering model using the K-Means algorithm is done. Their experience of formation of the state policy directed for support of innovative transformations of agrarian and industrial complex is generalized and recommendations on implementation of their best achievements in the domestic agricultural sector are offered. The aim of the work is a comprehensive assessment of innovative transformations taking place in the agricultural sector in the context of the challenges of global sustainable development. The task of the research is to determine the most successful group of countries in terms of implementation of intensification of production activities, the effectiveness of innovation policy and the ability to meet the demand for food, taking into account the requirements of sustainable development; providing recommendations for the modernization of agricultural production of domestic producers. The following methods of scientific research were used to achieve the goal and solve the problems of the article: system analysis, forecasting, generalization, modeling, namely clustering by the K-Means algorithm, etc. The scientific novelty of the obtained results is to provide comprehensive recommendations for the formation of domestic public policy aimed at supporting innovative transformations in the agro-industrial sector, based on key factors and determinants of its development and taking into account the best practices of leading countries in this field.

Keywords**:** agricultural production, innovations, sustainable development, state support.
JEL Classification O13, O39, Q01, Q17, F63
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ІННОВАЦІЙНІ ТРАНСФОРМАЦІЇ АГРОПРОМИСЛОВОГО КОМПЛЕКСУ В КОНТЕКСТІ ГЛОБАЛЬНИХ ВИКЛИКІВ СТАЛОГО РОЗВИТКУ

Анотація. Визначено, що забезпечення продовольчої безпеки і здорового харчування для зростаючого населення планети залишатиметься викликом для світової спільноти. Проаналізовано глобальні домінанти і тенденції розвитку агровиробничої діяльності в межах глобального ринку агропродовольчої продукції. Здійснено групування країн-лідерів із високоінноваційним агропромисловим сектором, що формується з урахування цілей сталого розвитку на основі побудови моделі кластеризації з використанням алгоритму K-Means. Узагальнено їхній досвід формування державної політики, спрямованої на підтримку інноваційних трансформацій АПК. Метою роботи є комплексна оцінка інноваційних трансформацій, які відбуваються в аграрній сфері в контексті викликів глобального сталого розвитку. Завданням наукового дослідження є визначення найбільш успішної групи країн щодо впровадження інтенсифікації виробничої діяльності, ефективності здійснення інноваційної політики і спроможності задоволення попиту на продукти харчування з урахуванням вимог сталого розвитку; надання рекомендацій щодо модернізації агровиробничої діяльності вітчизняних товаровиробників. Для досягнення мети і вирішення завдань були використані такі методи наукового дослідження: метод системного аналізу, прогнозування, узагальнення, моделювання, а саме кластеризації алгоритмом K-Means. Наукова новизна одержаних результатів полягає в наданні комплексних рекомендацій щодо формування вітчизняної державної політики, спрямованої на підтримку розвитку інноваційних трансформацій в агропромисловому секторі, ґрунтуючись на ключових факторах і детермінантах його розвитку та врахуванні передового досвіду країн-лідерів у цій сфері.

***Ключові слова*:** агровиробництво, інновації, сталий розвиток, державна підтримка.
Формул: 0; рис.: 2; табл.: 2; бібл.: 20.

Introduction. Modern global progress is characterized by a significantly growing global demand for food and changing consumer preferences with the simultaneous intensification of urban processes, scarcity of natural resources and pressure on ecosystems and so on. In such conditions, ensuring food security and defining the mechanism for achieving the goals of sustainable development become especially important. In view of this, more acute became the issue of radical revision of world models of food production and consumption and re-equipment of the agro-industrial sector on the basis of innovative vector of development, which is the main driver of simultaneous productivity growth and sustainable use of resources, modernization of infrastructure, inclusion in global value chains and farms, tackling poverty and hunger, reducing inequality, mitigating climate change, protecting ecosystems, and so on. These aspects actualize the scientific and applied search within the selected research topic.

Analysis of research and problem statement. A number of foreign and national scientists, in particular B. Burkynskyi, V. Heiets, P. Drukker, D. Lukianenko, L. Mykhailova, O. Poruchnyk, B. Paskhaver, M. Porter, A. Poruchnyk, P. Sabluk, I. Taranenko, A. Filipenko, O. Yatsenko and others, have made a significant contribution to the study of innovative transformations in the agro-industrial sector and the development of scientific and practical recommendations for ensuring compliance of public policy with the challenges of global sustainable development. At the same time, paying tribute to the scientific work of these researchers, it is necessary to further in-depth study of the modernization of the agricultural sector in accordance with the requirements of sustainable development.

The purpose of the article is a comprehensive assessment of innovative transformations taking place in the agricultural sector in the context of the challenges of global sustainable development.

Unsolved aspects of the problem is to substantiate the directions of further modernization of domestic agricultural production in accordance with the requirements of sustainable development.

Research results. The development of the global economic system, in particular in the field of agricultural production, is under the influence of a number of technological, institutional, social and environmental determinants. In the medium-term horizon, the main trends in the formation of international agri-food markets will be determined by a turbulent environment with closely intertwined goals in three dimensions of sustainable development — economic, social and environmental. Improving agricultural productivity is a key factor in ensuring the food security of the world's growing population, which, according to FAO, will reach 8.5 billion by 2030. At the same time, global demand for agricultural products will grow by 1.2% per year over the next decade, and overall food availability will increase by 4% over the same period, reaching just over 3,000 calories per person per day [1]. In addition, the processes of urbanization and aging of the world's population are currently being intensified, accompanied by the transformation of food systems and the socio-economic structure of rural communities. The change in the diet is projected to increase the consumption of poultry and dairy products, taking into account the consumer preferences of the population of South Asia. Achieving this level of food security will be due to increased global agricultural production, namely the growth of yields and productivity, expanding land use and the introduction of innovative achievements in the production process [2]. In these conditions, the modernization of the agro-industrial complex is one of the key levers of its formation in accordance with the goals of sustainable development. However, despite the fact that, according to forecasts, over the next ten years, emissions per unit of output will be significantly reduced, their total volume will increase by 4% [1]. These circumstances confirm the urgency of further innovative development in the field of agricultural production.

Some redistribution of production capacity within the developing country is expected. They will be increasingly involved in shaping the global agricultural and food market [3], and their share of exports will reach one third. Nevertheless, imports will account for a significant share of total domestic consumption in the Middle East and North Africa, Latin America and the Caribbean. Therefore, further development of international trade relations will continue to be crucial to global food security and poverty reduction in rural areas. The role of well-functioning markets in stimulating economic growth is significant, but the market mechanism cannot guarantee a number of social and environmental benefits that are key to sustainable development. This factor became especially relevant in the context of the COVID-19 pandemic, which was accompanied by failures at all stages of food supply chains [5]. Despite these shocks, overall trade in agri-food and global value chains has remained stable. Government measures to restrict exports and imports, change import barriers, and / or impose domestic trade restrictions have generally been short-lived.

The investment and innovation environment of the agricultural sector is important, but not always characterized by coherence and systematic measures taken by public authorities [6]. With

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this in mind, we have built a clustering model to identify the most successful group of countries in terms of implementing intensification of production activities, the effectiveness of innovation policy and the ability to meet food demand, taking into account the requirements of sustainable development. To this end, a number of indicators (*Table 1*) provided by FAO for 2019 have been developed [7].

Table 1

Statistical analysis of the original DataFrame for cluster modeling

Indexes	Statistical indicator							
	count	**mean**	**std**	**min**	**25%**	**50%**	**75%**	**max**
GDP per capita, US dollars	187	21365.7	22466.4	751.7	4918.1	13527.4	30358.2	127162.0
Index of political stability and absence of violence / terrorism	187	-0,04	0,93	-2.65	-0.56	0.01	0.75	1.66
Gross fixed capital formation	187	2241,04	7006,58	0.20	62.61	395.26	1469.19	65927.09
Percentage of the population that has access to quality drinking water	187	75.84	24.38	5.60	73.40	83.50	91.90	99.00
Energy value of food	187	1832.24	84.84	1661.0	1758.0	1840.00	1908.00	2059.00
Average adequacy of food energy supply (percentage) (average for 3 years)	187	121.67	15.05	79.00	113.00	123.00	132.00	158.00
Agricultural lands used under organic agricultural production	187	390.88	2646.45	0.00	5.03	27.83	112.05	35687.80
Use of pesticides on the area of crops	187	61.41	55.50	0.00	22.76	54.52	78.41	386.69
State support for agricultural development	187	62485.57	246494.5	0.01	12556.59	12700.5	12844.41	2901100.0
State support in the sphere of environmental protection (Central Government)	187	324.14	1001.78	0.00	106.67	106.67	106.67	9410.39

These indicators were selected from various data sets that characterize such areas of countries as economic, social, environmental and reflect, in particular, investment and technical equipment of agricultural production. This simulation was implemented on the basis of DataFrame libraries Pandas, Matplotlib, NumPy and others. The input data set is characterized by the statistics shown in *Table 1*. Data sets of this type mostly contain missing values represented by NaN. We replaced them with the weighted average value. A correlation analysis was performed to identify the likely relationship between the selected indicators. The most common is to determine the Pearson correlation coefficient, which compares two interval variables or variable ratios. The results of its calculation for the studied data set are shown in *Fig. 1*.

Units are on the main diagonal of the correlation matrix, as the correlation of the feature with itself is equal to one. Based on the pairwise analysis of correlations, we can conclude that the data set is not characterized by multicollinearity. Therefore, the data set can be used to build a model.

We have built the K-Means model, which is one of the simplest and most commonly used clustering algorithms. The input data was normalized to use this method. The model algorithm alternately performs two steps: assigning each data point to the nearest cluster center, and then setting each cluster center as the average of the data points assigned to it. Operation of the algorithm is such that it seeks to minimize the standard deviation at the points of each cluster. The basic idea is that at each iteration, the center of mass is recalculated for each cluster obtained in the previous step, then the vectors are divided into clusters again according to which of the new centers was closer to the selected metric. The algorithm ends when there is no change of clusters in any iteration [8]. The most common way to measure distances is the sum of the square error. To execute the algorithm at the input, among other things, the model must reflect the number of clusters. The Elbow method was used for this purpose (*Fig. 2*).

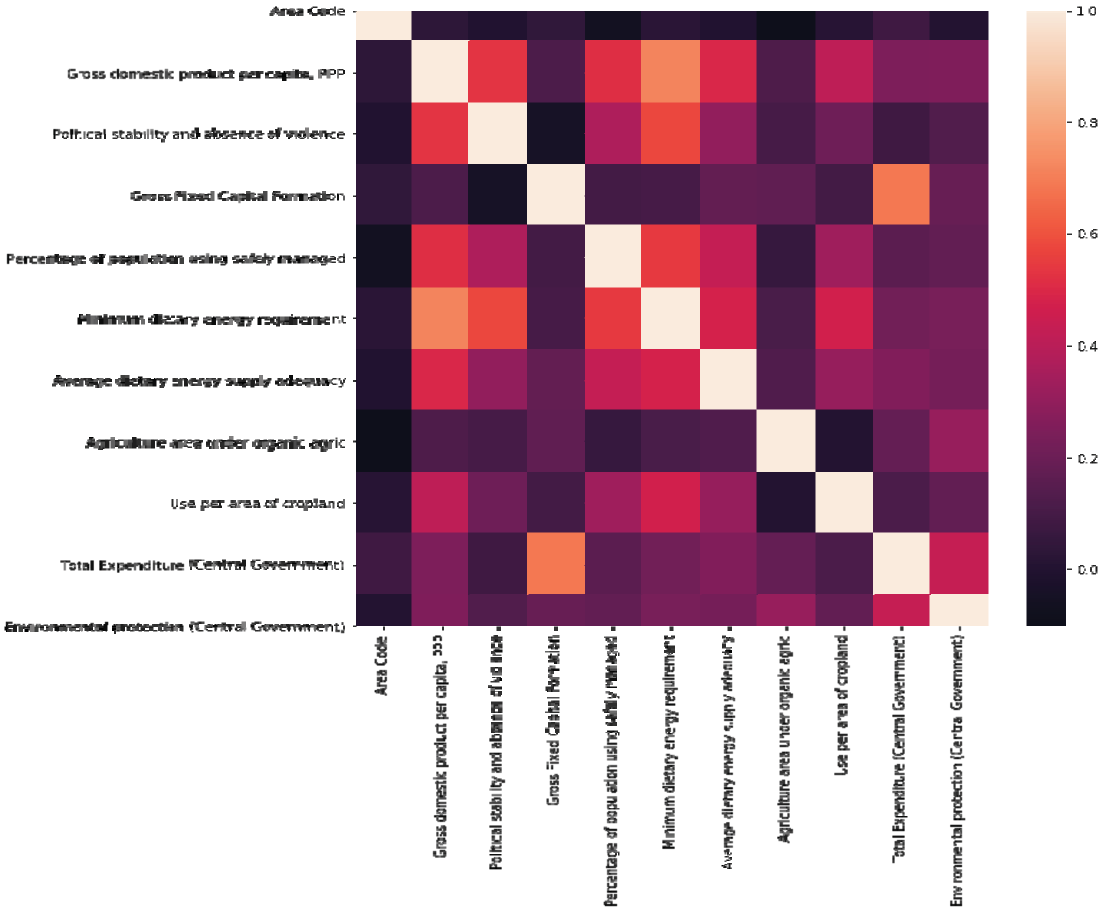

Fig. 1. **Correlation matrix of selected indicators for cluster modeling**

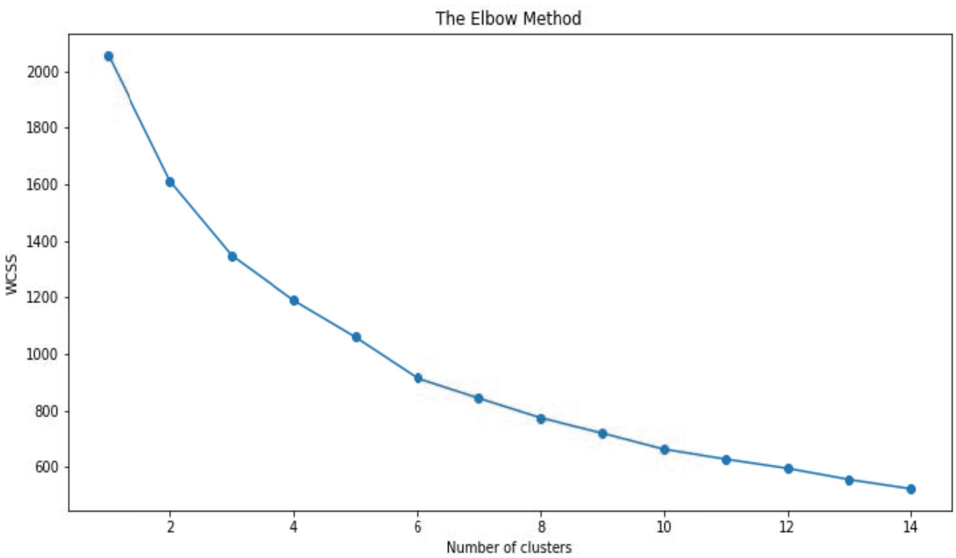

Fig. 2. **Determining the number of clusters based on the Elbow method**

The Elbow method consists of plotting the function change graph from the number of clusters and, as a result, selecting the number of clusters to use. Based on the obtained results, the optimal use of the division of countries into 4 clusters was determined. The centers of clusters in the context of the selected input data are given in *Table 2*. According to them, the algorithm assigns countries to groups. Based on the modeling, the studied countries were divided into 4 clusters (in total, the model included data on 187 countries).

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Table 2

The results of clustering modeling by the K-Means algorithm

Indexes	Clusters			
	1	2	3	4
Number of countries	82*	61**	40***	4****
GDP per capita, US dollars	11966.80	44817.61	4105.81	51593.28
Index of political stability and absence of violence / terrorism	0.03	0.56	-1.04	0.56
Gross fixed capital formation	1221.71	1895.39	2440.71	20803.03
Percentage of the population that has access to quality drinking water	76.76	93.57	48.55	95.52
Energy value of food	1819.89	1913.22	1737.32	1925.60
Average adequacy of food energy supply (percentage) (average for 3 years)	120.23	132.40	108.07	140.00
Agricultural lands are used for organic agricultural production	100.25	321.17	100.79	8402.33
Use of pesticides on the area of crops	42.97	106.84	30.41	102.44
State support for agricultural development	18774.95	70498.90	12029.16	1112917.43
State support in the field of environmental protection (Central Government)	159.19	331.33	79.67	5031.15

* *Cluster 1* (Albania, Algeria, Angola, Antigua and Barbuda, Argentina, Azerbaijan, Bangladesh, Barbados, Belarus, Belize, Benin, Bhutan, Bolivia (multinational state), Bosnia and Herzegovina, Botswana, Cape Verde, Cameroon, Cameroon, Comoros, Djibouti, Dominica, Dominican Republic, Ecuador, El Salvador, Equatorial Guinea, Esvatini, Fiji, Gabon, Georgia, Ghana, Grenada, Guinea, Guyana, Haiti, Honduras, Indonesia, Iran, Islamic Republic of , Kiribati, Kyrgyzstan, Malawi, Malaysia, Maldives, Marshall Islands, Mauritania, Mexico, Micronesia (Federated States of), Mongolia, Morocco, Namibia, Nauru, Northern Macedonia, Palau, Panama, Paraguay, Peru, Republic of Moldova, Russia, Keats and Nevis, Saint Lucia, Saint Vincent and the Grenadines, Samoa, Senegal, Serbia, Seychelles, Solomon Islands, South Africa, Sri Lanka, Suriname, Thailand, Timor-Leste, Tonga, Tunisia, Turkmenistan, Ukraine , Uzbekistan, Vanuatu, Vietnam);

** *Cluster 2* (Australia, Armenia, Austria, Bahamas, Bahrain, Belgium, Bermuda, Brazil, Brunei Darussalam, Bulgaria, Canada, Chile, China, Costa Rica, Croatia, Cyprus, Czech Republic, Denmark, Egypt, Estonia , Finland, Greece, Hungary, Iceland, Ireland, Israel, Italy, Japan, Kuwait, Latvia, Lithuania, Luxembourg, Malta, Mauritius, Montenegro, Netherlands, New Zealand, Norway, Oman, Poland, Portugal, Puerto Rico, Qatar, Republic Korea, Romania, Saudi Arabia, Singapore, Slovakia, Slovenia, Spain, Sweden, Switzerland, Trinidad and Tobago, Turkey, United Arab Emirates, Uruguay);

*** *Cluster 3* (Afghanistan, Burkina Faso, Burundi, Cambodia, Central African Republic, Chad, Congo, Democratic Republic of the Congo, Ethiopia, Gambia, Guatemala, Guinea-Bissau, India, Iraq, Kenya, Lao People's Republic) , Lesotho, Liberia, Libya, Madagascar, Mali, Mozambique, Myanmar, Nepal, Nicaragua, Niger, Nigeria, Pakistan, Palestine, Papua New Guinea, Philippines, Rwanda, Sao Tome and Principe, Sierra Leone, Sierra Leone Sudan, Tajikistan, Togo, Uganda, the United Republic of Tanzania, Zambia, Zimbabwe);

**** *Cluster 4* (France, Germany, United Kingdom of Great Britain and Northern Ireland, United States of America).

The 4th cluster turned out to be the smallest and included the group of countries with the highest indicators of efficiency of innovation policy in the agro-industrial sector, characterized by high yields, low share of resource costs, and high living standards. A characteristic feature of these countries is the significant cost of innovative development and research [9]. The other three clusters are quite numerous and need further elaboration in subsequent studies. Defining approaches to the formation of public policy in the group of cluster 4 countries in the field of innovative development of the agro-industrial sector and the corresponding impact on their sustainable development will provide an opportunity to outline recommendations for implementing best practices in domestic realities.

United States agriculture has a long history of being a world leader in the use of innovative approaches and technologies. Relying on the introduction of the latest advances in science and technology, such as artificial intelligence, robotics, biotechnology and nanotechnology, the country is able to achieve food security for a growing population. The main goals set by the US Department of Agriculture under the Agricultural Innovation Program are to achieve economic, environmental, social sustainability and, in particular, to increase agricultural production by 40% while halving the environmental burden by 2050 [10; 11]. The key to achieving the goals of the program is the introduction of the latest achievements of scientific and technological progress, as well as the active use of the achievements of the international division of labor, globalization, processes of cooperation and integration of production, digitalization and so on. The issue of establishing business on the latest principles also remains not without attention. US government support mechanisms are quite diversified [12] and cover four key areas, namely the creation of conditions for: stimulating private investment (reducing transaction costs of farmers; increasing investment in strategic infrastructure; simplifying the tax system, etc.); implementation of sustainable agricultural production (revision of regulations as to responding to the development of science and technology; increasing the efficiency of training skilled workers in the sector, etc.); strengthening the food and agricultural innovation system (support and modernization of research capacities in the field of food and agriculture; strengthening mechanisms for effective natural resource management; implementation of climate change strategy; financing and improving investment monitoring tools in the studied sphere) and conducting favorable agricultural policy for sustainable growth of farms (reform of commodity programs and other support measures to reduce commodity imbalance; strengthening the role of the federal government in solving subnational environmental problems; strengthening the principle of «polluter pays»; forming an information base to monitor the effectiveness of public policy, etc.).

The formation of innovative development of agricultural activity in France, Germany and Great Britain takes place within the framework of the implementation of the multi-purpose common agricultural policy of the European Union. Within them, a system of economic, social, and political levers of state support has been established. An important area of implementation of the EU's common agricultural policy under the Next Generation EU program, agreed by the European Parliament and the Council of the EU within the long-term budget for 2021—2027, is systemic greening combined with innovation and clustering of regional agro-industrial complex with large and small farms, the implementation of effective mechanisms of production cooperation and corporatization [13]. Achievements are widely used to improve infrastructure, logistics, and thus reduce transportation and communication costs. By improving the efficiency of value chains, a high level of food security in terms of its quantitative and qualitative criteria has been achieved within these countries, which also includes extensive tools for building a competitive market environment and introducing innovative forms of business organization.

Thus, analyzing results of the analysis of the policy of the countries included in the 4th cluster of the model it can be concluded that innovative development can be achieved if there is a close link between research, production, sales and service and with an effective system of state support. That is, the connection of the subjects of a single process throughout the value chain with a strong financial base. The formation of innovation-oriented models of development of the agricultural sector requires transformations in its institutional environment.

The modern agricultural sector of Ukraine's economy represents a crucial sector of material production, forming the core of ensuring food security of the state, increasing the level of material well-being of citizens and the development of domestic export potential. In recent years, the domestic agricultural sector is characterized by positive changes, namely: strengthening the capacity to provide agri-food products to the population [14], maintaining leading position of producers in the international arena for a number of product groups, diversification of agricultural production and export to agricultural markets [15]; dynamic renewal of machine and tractor fleet and introduction of innovative technologies in agricultural production processes [16; 17]; dissemination of environmentally friendly technologies of agricultural production, in particular organic technology [18], consistent implementation of priority areas of sustainable development of the national economy and its structural components, etc. [19; 20]. There is a tendency to further spread the latest technologies in the studied sector of the economy in order to increase productivity, promote economic intensification and job creation, and so on. In view of this, further systematic work should be carried out on the formation of areas to support the development of innovative transformations in the agro-industrial sector of Ukraine. In particular, mechanisms for financing innovation need to be established, including stimulating private investment in production technologies, streamlining the institutional component, implementing an infrastructure development strategy, realizing flexible labor and migration policies, and improving the functioning of agri-food markets; audit of ecological regulation of agriculture; strict protection of intellectual property, etc. This state of affairs requires significant improvement of the existing mechanisms of functioning of

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the agro-industrial sector and its transfer to the model of sustainable development with the maximum convergence of economic, social and environmental goals of social development.

Conclusion. The main trends in the global environment now are the shift of trade in agri-food products from surplus to deficit regions; change of consumer preferences; population growth and growth of its purchasing power; increasing the load on ecosystems, etc. In such conditions, a high level of innovation and a balanced policy to support agricultural production at the state and supranational levels are the key to achieving food security for the world's population. According to the study, the USA, France, Great Britain and Germany are among the group of countries with the highest indicators of efficiency in implementing the policy of innovation in the agro-industrial sector. Within the borders of these countries innovation is one of the most important factors in increasing the competitiveness of agriculture in the global agri-food market, increasing GDP and developing national production. The implementation of the best achievements in the modernization of the agro-industrial complex of these countries will provide an opportunity to develop an effective domestic state policy in this area. Given the available potential and highly competitive positions of domestic producers in a number of commodity positions of the agricultural sector, Ukraine can take on the task of becoming one of the main suppliers of food to the world market. This task can be achieved in the case of fairly rapid implementation of innovations in agriculture.

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