ISSN: 2221-1055
E-ISSN: 2413-2322

Національний науковий центр «Інститут аграрної економіки»

ЕКОНОМІКА АПК

Науково-виробничий журнал

Заснований у 1994 році
Випускається 6 разів на рік

Том 32, № 5

Київ – 2025

Рік заснування: 1994

Рекомендовано до друку та поширення
через мережу Інтернет Вченою радою
Національного наукового центру «Інститут аграрної економіки»
(протокол № 11 від 01 жовтня 2025 р.)

Рішення Національної ради України
з питань телебачення і радіомовлення № 1498,
протокол № 15 від 09.05.2024.
Ідентифікатор медіа – R30-04656.

Журнал входить до Переліку наукових фахових видань України
Категорія «А». Спеціальності: С1 (051) – Економіка, D1 (071) – Облік і оподаткування,
D2 (072) – Фінанси, банківська справа, страхування та фондовий ринок, D3 (073) – Менеджмент,
D7 (076) – Підприємництво та торгівля
(наказ МОН України від 24 лютого 2025 року № 349)

Журнал представлено у міжнародних наукометричних базах даних,
репозитаріях та пошукових системах: Google Scholar, Фахові видання України, Національна бібліотека України імені В. І. Вернадського, Crossref, AGRIS, German Union Catalogue of Serials, Econlit, ECONBIZ, UCSB Library, ZBW, WorldCat, JournalFinder, EZB, Litmaps, Ulrichsweb Global Serials Directory, InfoDase, PBN, UBL, COPE, TIB, I2OR, BASE, ERIH PLUS, EBSCO, Open Ukrainian Citation Index, EuroPub, Dimensions, University of Oslo Library, University of Hull Library, Search Oxford Libraries Online, European University Institute, Cambridge University Library

Адреса редакції:
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ISSN: 2221-1055
E-ISSN: 2413-2322

National Scientific Centre "Institute of Agrarian Economics"

EKONOMIKA APK

Founded in 1994
Published six times per year

Volume 32, No. 5

Kyiv – 2025

Year of foundation: 1994

Recommended for printing and distribution
via the Internet by the Academic Council
of the National Scientific Centre "Institute of Agrarian Economics"
(Minutes No. 11 of October 01, 2025)

Decision of the National Council
of Television and Radio Broadcasting of Ukraine No. 1498,
Minutes No. 15, dated 09.05.2024.
Media identifier – R30-04656.

Journal is included in the List of Scientific professional publications of Ukraine
Category "A". Specialties: 0311 – Economics, 0411 – Accounting and Taxation, 0412 – Finance, Banking and Insurance, 0413 – Management and Administration, 0416 – Wholesale and Retail Sales
(order of the Ministry of Education and Science of Ukraine No. 349 dated February 24, 2025)

Journal is presented international scientometric databases, repositories and scientific systems: Google Scholar, Professional publications of Ukraine, Vernadsky National Library of Ukraine, Crossref, AGRIS, German Union Catalogue of Serials, Econlit, ECONBIZ, UCSB Library, ZBW, WorldCat, JournalFinder, EZB, Litmaps, Ulrichsweb Global Serials Directory, InfoDase, PBN, UBL, COPE, TIB, I2OR, BASE, ERIH PLUS, EBSCO, Open Ukrainian Citation Index, EuroPub, Dimensions, University of Oslo Library, University of Hull Library, Search Oxford Libraries Online, European University Institute, Cambridge University Library

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ЗМІСТ /CONTENTS

Received: 02.06.2025. Revised: 02.09.2025. Accepted: 01.10.2025.

EKONOMIKA APK

https://doi.org/10.32317/ekon.apk/5.2025.10
Ekonomika APK, 32(5), 10-24

UDC 338.330.3

Food crisis in the modern world: Causes and possible consequences for Ukraine

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► **Abstract.** The prevention of the emergence and escalation of food crises in each country depended on the timely identification of their characteristic warning signs in order to protect food security. The study aimed to identify and summarise the causes and consequences of food crises in Ukraine and worldwide for preventing their occurrence and mitigating their negative impacts. The study revealed the specific features of the systemic vulnerability of food systems. It substantiated that the multidimensional and multidirectional nature of simultaneous global crises (financial, energy, environmental) created a synergistic polycrisis, with the food crisis as one of its components. Using the Ishikawa diagram, it was identified the cause-and-effect relationships leading to Ukraine's food crisis and structure the causes into major categories. The article established that potential causes of a food crisis and declining food security in Ukraine may include: the unresolved consequences of past crises; the global pandemic; manifestations of global economic shocks (rising world food prices, slowdown in agricultural production growth, declining global grain reserves, high energy prices, global population growth); the environmental crisis and extreme weather events; wars; local sectoral crises, such as the crisis in the dairy industry. Between 2020 and 2024, amid the COVID-19 pandemic and russia's full-scale invasion of Ukraine, global food prices rose 2.7-fold, while wheat stocks fell to 272 million tonnes in 2023/2024 period. The results of the study showed that, given the existing agricultural, industrial, innovative, and scientific-production potential, the occurrence of critical famine in Ukraine was possible only under artificially created challenges: wars causing destruction of arable land, seizure of harvests, restricted access to food; global man-made and environmental disasters. Theoretical, methodological, and applied provisions regarding the causes and potential consequences of food crises in the modern world can serve as a source of scientific information for the development of food security strategies and programmes

► **Keywords:** polycrisis; hunger crisis; food security; synergistic impact; food supply; Ishikawa diagram

► **Suggested Citation**: Kovalenko, O., Bokiy, O., Yashchenko, L., & Lysenko, H. (2025). Food crisis in the modern world: Causes and possible consequences for Ukraine. *Ekonomika APK*, 32(5), 10-24. doi: 10.32317/ekon.apk/5.2025.10.

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▸ Introduction

The frequency of global crises and disasters on a global scale had been gradually decreasing during the 20th and the beginning of the 21st century, which was a consequence of the manifestations of globalisation processes: the interdependence of countries in the world economy; the openness of markets and international cooperation; the strengthening of the international division of labour; the intensification of competition. At the same time, these processes were exacerbated by threats, including the growth of the greenhouse effect and climate change, the use of nuclear energy and genetic engineering, the spread of disease epidemics, and socio-economic imbalances. Crises, throughout their history, have arisen as a result of military conflicts, environmental disasters, pandemics, and could be of an economic, financial, energy, or food nature. The causes and threats of a food crisis and the approaches to overcoming them were the focus of research by scholars worldwide. D. Graham (2024) examined the nature of imperial responses to food crises during the ancient Roman Empire. Here hunger was addressed, among other measures, through special projects that created employment opportunities and increased household incomes, notably the construction of the Portus harbor. T. Nakamura *et al.* (2024), in the context of the main factors influencing the global food crisis (the COVID-19 pandemic, the armed aggression of the russian federation in Ukraine, and global climate change), assessed the measures undertaken to counter the food crisis in Germany. Researchers concluded that perceptions of the causes of the food crisis vary according to income, education, and age.

Y.-I. Lee *et al.* (2024), based on experimental research, showed that disinformation on social media regarding food product quality can disrupt social stability, especially among vulnerable groups, and exacerbate the food crisis. Therefore, it was crucial to prevent the spread of misleading messages concerning the quality and properties of food products, and thus strengthen efforts to counter misinformation about the food crisis. A.M.T. Thow (2024) traced the dynamics of food insecurity and its underlying causes, and proposed approaches to addressing nutrition challenges during food crises. In addition to ensuring food availability, the researcher proposed strengthening the integration of nutrition issues into broader crisis-response measures, including trade policy, urban planning, agricultural investments, and public health. K.O. Ouko & M.O. Odiwuor (2023) assessed the factors driving the approach of food crises in African countries, as well as the consequences and causes of global food price volatility in developing nations. Scientists identified the pandemic, the war in Ukraine that disrupted international food supply chains and prices, and climate change as the main causes of the food crisis on the African continent.

Researcher B.R. Tukamuhabwa (2023) underscored the importance of managing risks in agri-food supply chains, particularly for developing countries. C.S. Tang (2025) assessed the crisis factors and proposed addressing the global food crisis through the implementation of technologies and innovations in agriculture. The author evaluated innovative technological solutions to mitigate the food crisis, particularly for smallholder farmers. A. Libert-Amico & R. Koloffon (2025) highlighted the challenges and opportunities facing food systems during crises. Key challenges included shocks, violence, conflicts, and weak institutions that impeded investment in crisis-response measures. Opportunities involved synergies between climate, peace, and humanitarian actions, as well as development measures aimed at fostering resilient food systems during food crises. M. Kalyvaki & D.Q. Spencer (2025) emphasised the importance of systems for timely management, knowledge sharing and crisis communication, for addressing crises and making effective managerial decisions at both the enterprise and supply chain levels. D.T. Gebeyehu *et al.* (2025) assessed, through a survey of various respondent groups, both the direct and indirect impacts of the pandemic on food security in Ethiopia. To prevent future food crises from potential pandemics, researchers proposed establishing targeted groups to mitigate the impacts of food crises and strengthening disease prevention measures that affected food security.

F. Santos *et al.* (2025) proved that the escalation of the global food crisis exacerbated by climate change, conflicts, and economic hardships, necessitated a comprehensive approach to addressing economic challenges. Researchers applied a regression model based on data from 113 countries, covering both pre- and post-pandemic periods, and found that substantial income disparities among different social groups exacerbated food insecurity and made it impossible to overcome the problem through economic growth alone. A. Rokopanos *et al.* (2025), based on multivariate models, examining the relationships between agricultural commodity prices and input prices identified notable differences in these relationships before and after the 2009 crisis and concluded that modern agricultural policies were insufficiently effective, reducing farmers' incentives, while weakening the resilience of the agricultural sector. H. Ballouk *et al.* (2024) assessed the factors influencing financial security resilience and the risks associated with climate change, which were similarly relevant to food supply chains. The purpose of the article was to analyse and summarise the causes and effects of food crises in Ukraine and globally, with the goal of preventing their occurrence and alleviating their negative impacts.

▸ Materials and methods

The research was based on general scientific, historical, and economic-mathematical methods of scientific knowledge. To assess the state of the agri-food sector and its transformations during crisis periods, the historical method was applied. To structure the manifestations of polycrisis factors, as well as the consequences of a potential food crisis in Ukraine, the method of systemic generalisation was used. To identify differences in the behaviour of the food market under the influence of crisis phenomena, statistical methods were employed: the correlation-regression method – to establish interdependence and relationships between food production indicators and macroeconomic indicators; the index method – to analyse global price indicators, assess the impact of crisis factors on food costs, as well as on average global energy prices; grouping and comparison – to analyse employment in the agro-industrial sectors and to classify indicators by types of food products, production industries, and types of activities; and time series analysis – to examine changes over time in the sown area by types of agricultural crops. The balance method was used to assess supply and demand in the global grain market. The tabular method was employed to systematise and generalise datasets on food production and consumption, price fluctuations, and employment. The graphical method was applied to visually represent the development trends of the agro-industrial complex and the emergence of crisis phenomena.

For a comprehensive analysis of the factors causing food crises in Ukraine, their cause-and-effect relationships, and the associated risks, the Ishikawa (fishbone) diagram method was employed. The diagram was structured by categorising causes into major groups, represented as the "bones" of the fish skeleton. More specific causes, which provided a detailed description of the cause-and-effect relationships within each category, were placed along the smaller branches. The completed diagram made it possible to identify and visually document the of the problem under study. The information base of the research included: reports of the Food and Agriculture Organization of the United Nations (FAO), specifically FSIN & Global Network Against Food Crises (2023; 2024); materials of the World Food Programme, such as data from FAO *et al.* (2024). Also, it was analysed publications of the United States Department of Agriculture – articles by R. Trostle (2008) and S. Morgan *et al.* (2022) and materials of the World Economic Forum in Davos (Serhan, 2023; Guterres, 2023). To analyse food security and determine its scale in individual countries, the Integrated Food Security Phase Classification (IPC) (2008), recognised as an international scientific standard, was analysed. To reveal the main manifestations of polycrisis factors and the consequences of a possible food crisis, the database of the State Statistics Service of Ukraine (n.d.) was used.

▸ Results and Discussion

The main manifestation of food crises was the deterioration of food security, when the absence or shortage of food became the cause of malnutrition or hunger. FAO defined a food crisis as a situation of severe food insecurity that cannot be addressed using local resources and capacities alone, and that required urgent action to protect and save lives, as well as to preserve livelihoods at the local or national level. A food crisis was considered large-scale if more than 1 million people or more than 20% of the country's total population were affected by high levels of severe food insecurity. This level of crisis, according to the IPC developed by the FAO, referred to the third phase or "crisis" (acute food insecurity). If at least one region of the country experiences severe food insecurity, the situation was classified as a fourth phase or "emergency" (critical level of hunger) (FAO, 2024a). Severe food insecurity occurred, when a country's population was unable to consume enough food to sustain their lives and well-being. Food insecurity was assessed using internationally recognised indicators of acute hunger, as defined by IPC, which included five levels of food insecurity: 1) minimal food insecurity; 2) stressed food insecurity; 3) crisis (acute food insecurity); 4) emergency (severe hunger); 5) catastrophe or famine (this was the phase, when mass famine can be declared) (IPC, 2008).

Since the beginning of the development of agriculture, communities engaged in the production of agricultural products had experienced cyclical famines, the frequency, and intensity of which have changed throughout history, depending on changes in demand for food due to population growth, as well as changes in supply due to unstable climatic conditions. S. Devereux (2000) noted that according to expert estimates, from 70 to 120 million people died from famine around the world during the 20th century, more than half of them died in China: 30 million during the widespread starvation of 1958-1961; up to 10 million in 1928-1930; more than two million in 1942-1943. The Bengal famine of 1973 caused the deaths of an estimated 0.8 to 3.8 million people out of a population of 60.3 million (Sen, 1982). The major famines of the late 20th century also included the Biafran famine in the 1960s; the famine in Cambodia during the 1970s caused by the Khmer Rouge; the North Korean famine of the 1990s; the Ethiopian famine of 1983-1985.

The former Soviet Union lost 8 million people due to the famine of 1930-1933, over 1 million as a result of the famine of 1946-1947 and the blockade of Leningrad, and around 5 million during the famine of 1921-1923, including losses from the Holodomor on the territory of Ukraine. In the Soviet Union, the critical factors behind the 20th-century famines were: the lack of integration of historically famine-prone regions of a vast country due to underdeveloped communication and transportation networks; punitive economic policies (collectivisation of agriculture, state seizure of grain), and the genocidal policies of the country's top leadership against Ukraine. During the second half of the 20th century, the global food crisis was halted, and nutrition levels improved significantly in all regions. Despite the rapid growth of the world's population in the 1950s and 1980s, world grain production outpaced the rate of population growth, and meat and seafood production also increased. Between 1990 and 2019, the global prevalence of chronic undernourishment declined from 38% to 7.9% (Lee & Ghelani, 2023). N. Ryshkevych (2011) emphasised that the growth in grain production slowed down from 1990, in contrast to population growth.

Between 2001 and 2010, the risk of food crises intensified once again, threatening around 40 countries. One of the contributing factors was the growing energy dependence of nations, which led to the conversion of large areas of agricultural land in many European and American countries for the cultivation of energy crops intended for biofuel production, aimed at reducing the environmental impact of fossil fuels and decreasing reliance on them. Thus, the use of cereals and maize for biofuel production was six times higher than their use for food purposes, with a ratio of approximately 25 to 4 (%). At the same time, within a short period (1999-2008), global food prices rose sharply – by 98%, which led to hunger in many low-income countries. The overall commodity price index surged by 286%, while the crude oil price index increased by 547%. The situation was unprecedented, as the rise in prices for nearly all food commodities occurred simultaneously with record-high energy prices (Trostle, 2008; Mittal, 2009). The 2007-2008 crisis was dubbed the "triple F" crisis by the FAO because it was a consequence of the global food, fuel, and financial crises. In 2009, the number of people suffering from hunger rose sharply to over 1 billion, and the prevalence of hunger reached nearly 20% (FAO, 2011).

In 2020, at the beginning of the COVID-19 pandemic, FAO experts estimated that an average of 768 million people worldwide were facing food insecurity. The food problem hit countries in Asia, Africa, Latin America and the Caribbean the hardest, where the shares of undernourished populations were 55%, 37%, and 8%, respectively (Kernasiuk, 2022). In 2023, an average of 733 million people worldwide experienced undernourishment (first phase of food insecurity). Approximately 282 million people in 59 countries and territories faced high levels of acute hunger (fourth phase) in 2023, compared to 258 million people in 58 countries and territories in 2022 (FSIN & Global Network Against Food Crises, 2023). The FAO, the International Fund for Agricultural Development (IFAD), the United Nations Children's Fund (UNICEF), the World Food Programme (WFP), and the World Health Organization (WHO) predicted that if modern trends continue, approximately 582 million people will suffer from chronic undernourishment by 2030, with half of them residing in Africa. These projected figures were very similar to those from 2015, when the Sustainable Development Goals were adopted, and this was a concerning indication that progress has stalled (FAO *et al.*, 2024). The global food system, responsible for feeding billions of people, was under constant pressure from various triggers: climate change; armed conflicts; frequent shocks; global economic crises; and political instability, especially in low-income countries. These triggers disrupt global food supply chains, leading to massive food losses in some regions and acute shortages in others. This imbalance was exacerbated by the globalised nature of food supply chains, where approximately 20% of the world's dietary energy comes from imported products (Clapp & Cohen, 2009).

According to FAO estimates, global food production needs to increase by 70% over the next 40 years (by 2050) to feed the growing world population, which was expected to reach 9.3 billion (FAO, 2009a; Starychenko, 2019). Only resilient food systems will be able to withstand such a demand. However, the fact that food crises have occurred repeatedly since the 1970s indicated the vulnerability of the global food system and its susceptibility to disruptions caused by failures in other systems. For example, Ukraine alone was classified four times between 2018 and 2023 as a country experiencing a major food crisis, where at least one million people faced acute food shortages (FSIN & Global Network Against Food Crises, 2024). Crises of 2010-2025 have highlighted three key features of the systemic vulnerability of food systems:

- a limited range of staple crops involved in industrial food production;
- an imbalance between a small number of agricultural exporting countries and a large number of import-dependent countries;
- highly concentrated global agro-food and financial markets.

The world of 2020s was experiencing a major global food crisis characterised by rising hunger, where climate change intertwines with economic and financial crises, a health crisis, and a geopolitical crisis. Therefore, experts view the current food crisis as part of a broader problem – a polycrisis, which united other crises that cannot be separated due to their interconnected nature. The term "polycrisis" had been used to describe the complex interaction between crises and their consequences, and sometimes to justify the inaction of political leaders, international institutions, and the private sector, who continued to resist significant changes in their practices and conduct business, while typically maintaining a technocratic approach to poverty (Lawrence, n.d.). The term was firmly established at the annual meeting of the World Economic Forum in Davos, in January 2023 (Serhan, 2023). The report emphasised that "simultaneous shocks, deeply interconnected risks, and the undermining of resilience give rise to the risk of a polycrisis – where discrete crises interacted in such a way that the overall impact far exceeds the sum of each part". The term was used, among other things, to denote the potential scarcity of natural resources, including food raw materials, water, metals, and minerals.

S. Fedulova (2023) referred to the global crisis as multidimensional, emphasising that it was not equivalent to a polycrisis, as it does not have catastrophic consequences for the entire world. Its multidimensionality lies in the simultaneous impact of risks that emerged from global crises (financial, energy, food), specifically: the rising cost of living, geopolitical confrontation, the destruction of social cohesion, and societal polarisation. The author argued that the most serious risk was the unprecedented increase in the cost of living in the 21st century, occurring at a time, when people and countries had limited capacity to cope with the cascade of existing crises – the COVID-19 pandemic and climate change. An analytical review by the Canadian research centre Cascade Institute, which focused on emergent and systemic risks, highlighted key characteristics of a polycrisis. The first of these was the necessity of causal relationships between crises across different systems, which gave rise to side effects and amplify the crises (Is there life in a polycrisis…, 2023). The second was the simultaneous involvement of multiple systems in crisis; so, a polycrisis was defined as a situation "when three or more systems are in crisis at the same time". The third characteristic was that the "collective effect" resulting from the interaction of multiple crises cannot be compared to the sum of the effects these crises would have individually.

At the epicentre of the polycrisis were agriculture, the food industry, and the processing sector, which were highly vulnerable to extreme weather events and climate change-related phenomena, geopolitical shocks, natural resource scarcity, and biodiversity loss. These sectors faced a wide range of challenges that required urgent attention, including the pressing need for decarbonisation, to which the food production sectors were directly relevant (LaBrecque, 2023). The interconnected set of shocks and critical situations emerging simultaneously across various spheres of society undermined the resilience of food systems, increased their instability, and became the causes of a food crisis. For Ukraine, as well as for the global economy as a whole, food crisis that began in 2019 was the result of the synergistic impact of multiple triggers and, at the same time, part of a set of crises that collectively constituted a global polycrisis. Ukraine experienced the most terrible manifestation of the cost of living crisis due to the war imposed by russia, which significantly constrained household budgets as a result of rising food prices and a sharp decline in incomes, increased levels of poverty and hunger, negatively impacted education, and reduced access to energy. The 2022 russian invasion of Ukraine, occurring amid a polycrisis, also posed a significant threat to the global food system, as both countries were major exporters of grains. This led to a sharp surge in grain prices and volatility to record levels. The most vulnerable in this situation were the countries of Africa and the Middle East, which heavily depended on grain imports from russia and Ukraine. According to FAO (2022a) estimated, during this period, as a result of the war in Ukraine, approximately 20-30 million people in various countries worldwide faced hunger.

World Bank analysts predicted that if the war in Ukraine continues, by 2030 the number of chronically undernourished people worldwide will be approximately 23 million higher than if the war had not occurred (Emediegwu, 2024). Before the escalation of russian military actions in February 2022, the Eastern regions of Ukraine – Donetsk and Luhansk regions – were already experiencing a food crisis: as of 2021, approximately 383,000 people faced acute food insecurity. In total, during 2019-2021, 9.9 million people across the country experienced moderate or severe food insecurity according to the Food Insecurity Experience Scale, which measured chronic food insufficiency. The highest levels of food insecurity in 2022 were recorded in areas most affected by the war, particularly in the Eastern and Southern regions: 56% of the population in Luhansk, 50% in Kharkiv, 46% in Kherson, and 45% in Donetsk; as well as in the Northern regions: 45% of the population in Chernihiv and 41% in Sumy. In these regions, every second household was classified as food insecure (FAO, 2022b).

The agri-food sector of Ukraine has suffered significant since 2022 to 2025, negatively impacting both crop and livestock production domestically and on global markets. The migration crisis caused by the war had become the largest in Europe since World War II, with approximately 3.7 million internally displaced persons as of 2023 (FSIN & Global Network Against Food Crises, 2024). This has correspondingly reduced the labour potential of the food system, which, combined with high unemployment rates, has limited financial access to food. In 2023, over 7 million people in Ukraine faced acute food insecurity, especially in frontline areas of the Eastern and Southern regions. A comprehensive diagnosis of the key factors and causal relationships of the risks that led to the emergence of food crises in Ukraine was conducted in the study using the Ishikawa diagram (Fig. 1).

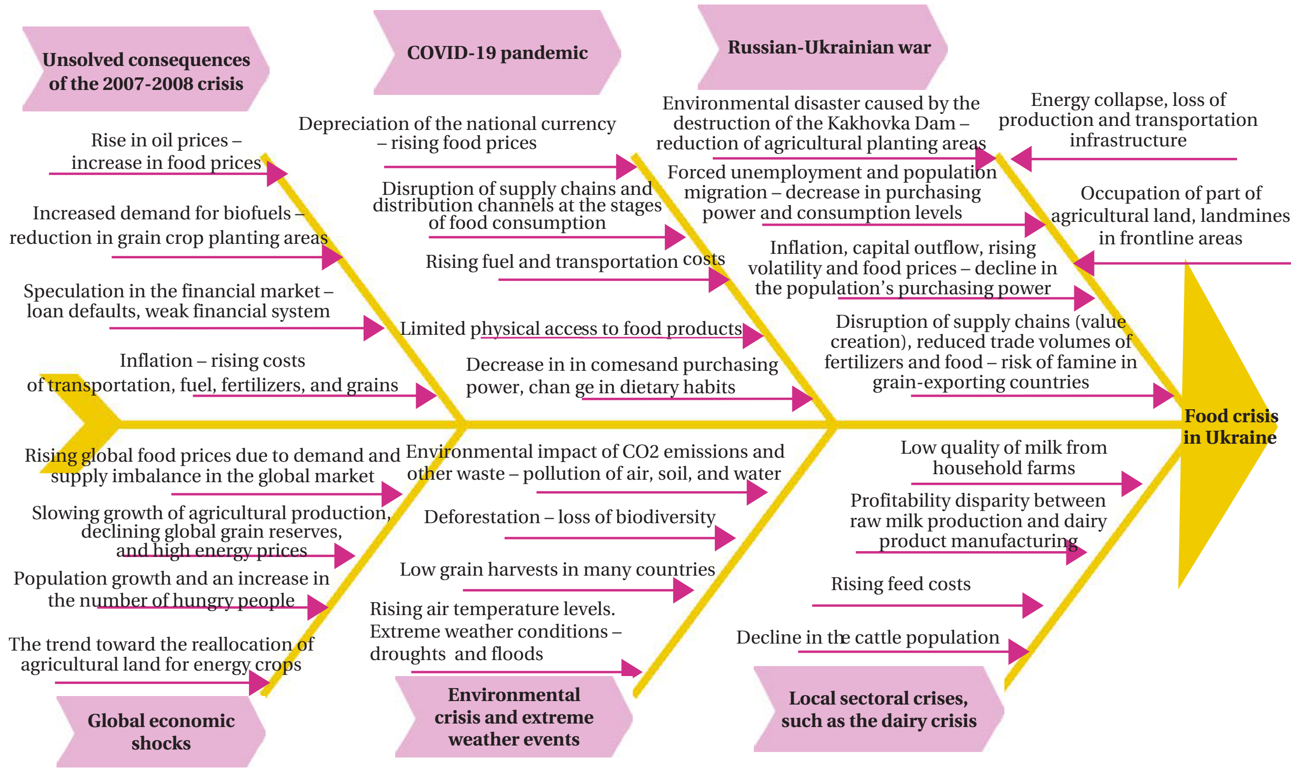


Figure 1. Ishikawa diagram showing the cause-and-effect relationships of a possible food crisis in Ukraine
Source: based on J. Ng (2025)

The global crisis of 2007-2008 became an unresolved consequence for Ukraine's food security. It was triggered by problems in the monetary and financial sectors of developed countries, which spread globally, leading to a decline in the USD exchange rate, inflation, and a reduction in household incomes in most countries around the world. The crisis caused not only significant economic losses but, together with other factors, also led to a prolonged stagnation of the Ukrainian economy. While during the period from 2000 to 2007 Ukraine's gross domestic product (GDP) grew at an average annual rate of 7%, in the period from 2008 to 2013 it dropped to 0.7% (World Bank Group, 2017). In 2014-2015, Ukraine experienced a double shock: the armed conflict with the russian federation and a decline in global commodity prices. During this period, the economy contracted by 8.2%

annually. In 2016-2021, GDP grew at an average annual rate of 1.9% (State Statistics Service of Ukraine, n.d.). The rise in the global oil price to USD 143 per barrel in 2008 led to an increase in food prices, as energy accounted for a significant portion of the costs of food production and transportation. At the beginning of 2008, the average world price of wheat rose to USD 481 per ton (FAO, 2009b). At the same time, during 2007-2008, there was a continued redistribution of agricultural land, with expanding areas dedicated to energy crops used for biofuel production.

In Ukraine, during 2007-2009, influenced by global trends, the increase in prices for fuel and lubricants, as well as natural gas (by 82% and 54% respectively), caused a significant rise in the cost of basic food products: sugar, butter, fruits, oils, and fats more than doubled in price; bread and bakery products increased by 71%; milk and dairy products by 93%; meat and meat products by 62%; fish and fish products by 58%; and eggs by 86% (State Statistics Service of Ukraine, n.d.). The 2007-2008 crisis demonstrated the strong financial interdependence, particularly in the agro-industrial sector, and low efficiency of the global financial system amid increasing globalisation and accelerated capital migration (Ortina, 2015). This crisis should have concluded with the transfer of financial resources accumulated by large businesses into new productions of the next technological paradigm, particularly in nanotechnology, biotechnology, and information technologies (Horkina, 2001). However, the process of recovery from the crisis had been prolonged and remained incomplete in many countries, including Ukraine. This had resulted in the emergence of new socio-economic challenges, including within the food sector. Specifically, rising oil prices drove up food prices; demand for biofuels produced from agricultural raw materials reduced grain cultivation areas. A fragile financial system and speculation in financial markets led to credit defaults; inflation caused increases in costs for logistics, fuel, fertilizers, seeds, grains.

In 2008 alone, in food production, sugar production decreased the most, with the production index at 80.9% in 2009, followed by processed vegetables and fruits at 83.1%. The crisis worsened the work of the agricultural sector due to rising credit rates and restricted access to credit necessary for sowing campaigns, modernisation of capacities and equipment purchases, as well as reductions in investments and demand for agricultural products in both domestic and foreign markets. The mitigation of negative consequences and the recovery from the crisis in Ukraine were facilitated by the implementation of a special VAT (Value Added Tax) regime and minimum purchase prices for grain for agricultural producers, the attraction of international financial aid, and other measures aimed at overcoming the adverse effects of the global crisis, which eased the mutual settlements of agricultural enterprises. Ukraine's accession to the World Trade Organization (n.d.) in 2008 accelerated its integration into the global economy.

Each crisis, the methods and means of overcoming it, revealed new opportunities for the country's economy and agricultural sector. Thanks to banking reforms implemented in 2009-2010 (strengthening banking supervision, monetary policy to prevent inflation and UAH devaluation, ensuring liquidity of the financial system) and in 2016-2017 (rehabilitation of insolvent banks, liberalisation of currency regulation, consolidation of the banking sector), the national currency and financial system withstood the full-scale invasion of the russian federation in Ukraine in 2022. The UAH devaluation in 2008-2009 contributed to the expansion of Ukrainian agricultural exports. The food sector proved to be the most resilient to the crisis among other economic sectors, owing to high grain yields and support for food exports (Kachur *et al.*, 2016; Vidyakin, 2017). The analysis of food market indicators trends during 2001-2010, which encompassed the crises of 2003-2004 and 2007-2009, revealed a correlation between food production indicators and the Ukraine's macroeconomic indicators (Table 1).

Table 1. Correlation coefficients between food production indicators and macroeconomic indicators in 2001-2010 in Ukraine

	Correlation coefficients of indicators				
	GDP, UAH billion	**Exchange rate, UAH/USD**	**Present population, thousand persons**	**CPI, % compared to the previous year**	**Direct investment, USD million**
Meat and meat products, thousand tons	0.92	0.64	-0.87	0.35	0.61
Milk and dairy products, million tons	-0.96	-0.70	0.85	-0.61	-0.62
Sugar, thousand tons	-0.50	-0.53	0.32	-0.39	-0.20
Bakery products with short shelf life, thousand tons	-0.98	-0.73	0.95	-0.49	-0.64
Sunflower oil, thousand tons	0.91	0.75	-0.92	0.34	0.55

Source: State Statistics Service of Ukraine (n.d.)

Correlation coefficients demonstrated a strong interconnection (both direct and inverse) between the country's GDP and the production of the analysed food products. The exchange rate showed the highest correlation with export-oriented sunflower oil. A significant dependence was observed between production indicators and the number of population (except for sugar). Regarding the inflation indicator, there was a sufficiently strong inverse relationship with the production of milk and dairy products. A fairly strong correlation was also evident between foreign direct investment and the production of most types of food products, with the exception of sugar, as sugar production was highly volatile and dependent on both global and domestic market conditions. Overall, the relationship between food production and macroeconomic indicators was quite strong and corresponded to the state of the economy of Ukraine. The negative impact of the global COVID-19 pandemic on Ukraine's food security manifested in rising food prices, complications in the logistics of raw materials and finished product supply (storage, transportation, and distribution of food to consumers), a reduction in the number of production personnel at food manufacturing enterprises, and decreased labour productivity. Despite the fact that Ukraine's food sector demonstrated considerably greater resilience to the impacts of the pandemic compared to other economic sectors, industrial production of food products declined on average by 6.2% during 2020-2021, primarily due to reductions in vegetable oils, sugar and sugar confectionery products, flour and tobacco products (Kovalenko & Bokiy, 2022).

Despite low inflation rates in 2020, Ukraine experienced significant price fluctuations in food products. Prices for long shelf-life products (such as cereals and flour) and butter increased at an accelerated pace. The price growth was influenced by logistical challenges, rising costs of raw materials and energy resources, as well as increased demand during quarantine measures. Prices of bread, sunflower oil, butter, milk, cheese, and meat increased significantly in 2021. Despite these challenges, indicators of adequacy of meat and dairy product consumption by the Ukrainian population remained practically unchanged (State Statistics Service of Ukraine, n.d.). Quarantine restrictions affected the export of meat products by complicating the conditions for livestock farming and processing, primarily of cattle. To mitigate the negative impacts of the pandemic, many countries, including Ukraine, implemented short-term and long-term planning and forecasting tools, improved food supply logistics, modernised storage facilities, and provided targeted food supply measures for low-income populations and regions with limited access. Ukraine had not yet fully recovered from the impacts of the pandemic on food security, as these challenges were further exacerbated in 2022 by a new wave of food-related problems caused by the full-scale invasion of Ukraine by the russian federation. The analysis of the correlation between food production and macroeconomic indicators over 2011-2021, which encompassed the 2014 military-political crisis in Ukraine and the COVID-19 pandemic in 2019-2020, indicated that the strength of the relationship between these groups of indicators changed compared to 2001-2010 years (Table 2).

Table 2. Correlation coefficients between food production indicators and macroeconomic indicators in 2011-2021 in Ukraine

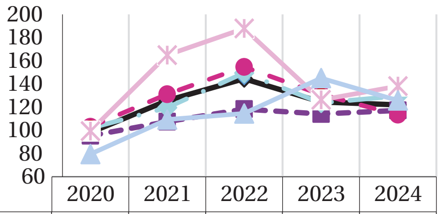
	Correlation coefficients of indicators (2011-2021)				
	GDP, UAH billion	**Exchange rate, UAH/USD**	**Present population, thousand persons**	**CPI, % compared to the previous year**	**Direct investment, USD million**
Meat and meat products, thousand tons	-0.56	-0.21	0.97	-0.99	0.32
Milk and dairy products, million tons	0.65	0.29	-0.99	1.00	-0.39
Sugar, thousand tons	-0.76	-0.46	0.80	-0.77	0.62
Bakery products with short shelf life, thousand tons	-0.60	-0.84	-0.04	0.16	0.38
Sunflower oil, thousand tons	0.91	0.75	-0.92	0.34	0.55

Source: State Statistics Service of Ukraine (n.d.)

The correlation between GDP and food production slightly decreased but remained. While in the 2001-2010 years the exchange rate correlated with the production of all analysed product types, in 2011-2021 the relationship was observed only with bakery products and sunflower oil. The strongest correlations were found between the production of dairy and meat products and inflation, as well as between dairy production and the number of population. The weakest correlation was observed between the production of bakery products and macroeconomic indicators (except for the exchange rate and GDP). The main measures to overcome the crisis caused by the pandemic were aimed at enhancing the resilience of the food system and addressing other crisis-related challenges. These measures included support for internal producers, diversification of food supply chains, promotion of local producers and food self-sufficiency among the population, improvement of legislation, and other initiatives. As a result, in 2021, Ukraine's annual production index increased to 102.8% for bakery products, 108.8% for fruit and vegetable processing, and 103.9% for meat and meat products (Bokiy, 2024; State Statistics Service of Ukraine, n.d.). Global economic shocks that reduce food security levels may arise from numerous factors. Since 2001, the primary factors have included: rising global food prices due to demand-supply imbalances; slowing growth rates in agricultural production; decreasing global grain reserves; high energy prices; increasing global population and number of people suffering from hunger; and the trend of reallocating agricultural land to energy crops for biofuel production.

So, the increase in global food prices due to the imbalance between supply and demand. According to estimates by the Ministry of Agrarian Policy and Food of Ukraine (n.d.), prior to the full-scale invasion by the russian federation, Ukraine supplied food to over 400 million people worldwide, excluding its own population. The country was a leading exporter of agricultural products to many countries in the Middle East and North Africa (Grigorenko, 2022). Disruptions in supply chains caused by russian aggression in 2022 led to an increase in the prices of staple food products in Ukraine, created an imbalance between global food supply and demand, and resulted in a 44%

surge in global food prices compared to their already elevated levels in 2021. According to FAO data, between 2020 and 2024, average global food prices rose by 2.7 times, including: meat and meat products – by 1.6 times; milk and dairy products – by 2.9 times; cereals – by 3.1 times; vegetable oils – by 5.4 times; and sugar – by 1.8 times (Fig. 2).



	2020	2021	2022	2023	2024
Food Price Index	98.1	125.7	144.5	124.5	122
Meat	95.3	107.5	118.3	114.1	117.2
Milk	101.8	119.6	149.5	123.7	129.6
Cereals	103.1	131.2	154.7	130.9	113.5
Vegetable Oils	99.4	164.9	187.8	126.3	138.1
Sugar	79.5	109.3	114.5	145	125.7

Figure 2. Global food price indices in 2020-2024, %
Source: FAO (2025)

Despite a slight decrease in global food prices in 2024 compared to 2022, prices have not returned to 2020 levels. Slowing growth in agricultural production, declining global grain reserves, and high energy prices. Global production of major agricultural crops reached 9.6 billion tones in 2022, representing a 56% increase compared to 2000. Key crops such as sugarcane, maize, wheat, and rice together account for nearly half of global agricultural output. Although food production continued to grow, the rate of growth was declining, and hunger remained a persistent issue (Martella, 2024). Findings from the United States Department of Agriculture's long-term assessment of annual global, regional, and national agricultural production and productivity indices (conducted since 1961) indicated that during 2011-2020 years, global agricultural output grew at its slowest pace – 1.93% annually, compared to 2.72% in 2001-2010s (Morgan *et al.*, 2022). This slowdown was primarily due to a deceleration in total factor productivity growth (including land, labour, capital, and material inputs), which declined to 1.14% annually in 2012-2021 from 1.93% in 2001-2011 years.

It was attributed these changes to several factors: 1) climate change, where extreme weather events (droughts, heavy rains) led to reduced crop yields; 2) emergence of new pests and diseases, which also negatively affected yields and required farmers to incur additional costs for control; 3) reduction in public investment in research and development, resulting in long-term declined in productivity (Chadde, 2023). According to estimates by the International Grains Council, the expected global grain stocks at the end of the 2024/2025 marketing year (MY) were projected to decrease by 5.2% (to 581 million tonnes) compared to the 2021/2022 MY. This change was driven by an increase in global grain consumption, which was expected in 2021/2022 to reach 2,326 million tonnes. Most of this increase was provided by corn consumption, which was projected to rise by 17 million tonnes (to 1,230 million tonnes). Despite an increase in wheat production volumes, global wheat stocks had declined during the 2021/22 to 2023/24 MY period to 272 million tones, with a further reduction to 267 million tones anticipated in the 2024/25 MY (Table 3).

Table 3. Balance of supply and demand for grains in the global market

Indicator	2021/2022	2022/2023	2023/2024	2024/September of 2025	2024/September of 2025 to 2021/2022, %
All cereal crops, million tonnes					
Production	2,293	2,267	2,304	2,316	101.0
Consumption	2,293	2,277	2,316	2,326	101.4
Ending stocks	613	603	591	581	94.8
Production-consumption balance, year-on-year	0	-10	-12	-10	x
Trade	427	428	455	421	98.6
Wheat, million tonnes					
Production	780	804	795	798	102.3
Consumption	784	794	807	803	102.4
Ending stocks	274	284	272	267	97.4
Production-consumption balance, year-on-year	-4	10	-12	-5	x
Trade	198	209	215	198	100.0
Corn, million tonnes					
Production	1,222	1,163	1,227	1,224	100.2
Consumption	1,213	1,184	1,223	1,230	101.4
Ending stocks	298	277	281	276	92.6
Production-consumption balance, year-on-year	9	-21	4	-6	x
Trade	181	180	195	181	100.0

Notes: x – not applicable
Source: IGC reports falling global grain stocks despite record production in 2024/25 (2024)

The results of the assessment of food security status, presented in Order of the Cabinet of Ministers of Ukraine No. 684-r (2024), indicated that the achieved level of domestic production development of agricultural products, raw materials, and food in Ukraine was capable of ensuring the physical availability of food products for the population at a daily energy equivalent level of 2,677-2,700 kcal per person. For comparison, the average daily caloric intake in EU countries ranges between 3,400 and 3,500 kcal. In addition to the consequences of the pandemic, the complex geopolitical situation, and weather conditions, energy prices significantly affected the level of food security. The energy intensity of food production, as well as the cost of electricity and gas, remained quite high and were incorporated into the final product price throughout the entire production and supply chain. The most energy-dependent industrial sectors in Ukraine in 2020 were ferrous metallurgy (15,216 GWh), the food industry (4,588 GWh), and the chemical sector (3,964 GWh). Interruptions in energy supply negatively affected the dairy, oil and fat, milling, bakery, and compound feed industries (Sobkevych & Shevchenko, 2023).

In the series of global economic, the deepening demographic crisis in Ukraine had a considerable impact on the formation of food security. The demographic crisis under wartime conditions posed a threat to food security by hindering access to food in frontline areas, increasing poverty among citizens, who had lost their jobs, and driving population migration, especially from rural regions, which simultaneously reduced the volume of agricultural production. In 2021, of the 1.4 billion hectares of land used for cultivating agricultural crops worldwide, about 8% was allocated for the production of raw materials used in biofuel manufacturing (Oils & Fats International, 2023). If the area of arable land dedicated to energy crops continues to expand, food security may be put at risk. At the same time, Oils & Fats International (2023) study have identified an increase in the value of highly productive arable land due to competition between food and biofuel production. So, it economically feasible to grow energy crops on arable land, as alternative solar and wind energy were even more expensive. Bioethanol was growing in popularity, its share of global biofuel production now exceeding 94%, as many countries replace part of their fossil fuels with biofuels in line with international regulations. In the European Union, the raw materials for bioethanol production were cereals and corn, as well as sugar beet and sweet sorghum (Skoufogianni *et al.*, 2019). By-products of biofuel production from agricultural crops were used in the food chain as high-quality protein feed additives, which reduced the demand for pure protein crops, in particular soybeans.

In Ukraine, during 2000-2021, the areas of agricultural land used for cultivating crops suitable for biofuel production, particularly rapeseed and sunflower, increased by 4.7 and 2.3 times (to 6,622.0 and 1,005.8 thousand hectares), respectively. During 2022-2024, amid the full-scale war of the russian federation against Ukraine, as a result of the occupation of part of its territory, the sown area for sunflower decreased by 25.3% compared to 2021 (to 4,947.4 thousand hectares), while that for rapeseed increased by 25.9% (to 1,265.9 thousand hectares). The areas cultivated with cereals, leguminous crops, and sugar beet, which can also serve as raw materials for bioethanol production, have changed variably. Between 2000 and 2021, the area under cereals increased by 17.2% (to 15,994.8 thousand hectares), while the area under sugar beet decreased by 73.5% (to 226.7 thousand hectares). During 2022-2024, the sown areas of cereals and leguminous crops declined by 30.5% (to 11,116.1 thousand hectares), sugar beet cultivation increased by 13.6% (to 258 thousand hectares). The area devoted to other energy crops in 2024 amounted to 3.5 thousand hectares, which was three times higher than in 2021 (Table 4).

Table 4. Sown area by species of agricultural crops in all agricultural holdings in Ukraine, thousand hectares

Crop	2000	2010	2015	2020	2021	2022	2023	2024	2021 to 2000, %	2024 to 2021, %
Cereal and leguminous crops	13,646.5	15,090.0	14,738.4	15,392.2	15,994.8	12,171.1	10,984.6	11,116.1	117.2	69.5
Industrial crops	4,186.8	7,295.8	8,350.3	9,223.8	9,244.5	8,292.2	8,909.7	9,257.1	220.8	100.1
Oilseed crops,including:	3,256.3	6,744.9	8,074.3	8,983.7	8,997.7	8,095.2	8,638.3	8,999.1	276.3	100.0
sunflower seeds	2,942.9	4,572.5	5,104.6	6,457.2	6,622.0	5,292.8	5,220.1	4,947.4	225.0	74.7
soya beans	64.8	1,076.0	2,158.1	1,351.0	1,310.8	1,558.9	1,842.1	2,655.5	2,022.8	202.6
winter rapeseed and colza (spring rapeseed)	214.3	907.4	682.4	1,126.6	1,005.8	1,185.7	1,435.6	1,265.9	469.3	125.9
mustard seeds	27.2	129.1	66.9	24.7	20.8	19.0	86.0	43.0	76.5	206.7
flax kudryash (oil)	2.3	58.9	62.2	13.8	27.7	33.1	47.5	54.1	1,204.3	195.3
Sugar beet (for processing)	855.6	500.9	237.4	220.0	226.7	184.1	250.3	258.0	26.5	113.8
Energy crops	…	…	…	c	1.1	2.5	2.2	3.5*	x	318.2

Notes: dots (…) – no data published; c – data are not released by the State Statistics Service of Ukraine in order to comply with the requirements of Ukrainian law; x – not applicable
Source: State Statistics Service of Ukraine (n.d.); W. Wichtmann & O. Denyshchyk (2024) for indicator marked with the (*) symbol

According to estimates by source Energy crops can be grown on 8 million hectares in Ukraine (2018), about 8 million hectares of land in Ukraine that were not used for growing traditional agricultural crops were suitable for cultivating energy crops, but only of the perennial bioenergy plants. Extreme weather events driven by climate change were causing significant harm to food security and the global economy. The rise in global temperatures led to an increase in the frequency and intensity of extreme weather events (such as frosts, hurricanes, typhoons, floods, and droughts), which affected agricultural productivity. The source Climate change will reduce grain yields by 23% – scientists (2017) predicted that due to global warming, which caused droughts and other extreme weather conditions, cereal yields may decline by 23% by 2050, and led to a decrease in the global production of major crops such as wheat, maize, rice, and soybean. Due to global warming and climate change, Ukraine was experiencing a shift in natural-climatic zones, with corresponding movement of warm-loving agricultural crop sectors toward the northern regions of the country, leading to a reorientation of agricultural activities. V. Rusan *et al.* (2024) emphasised that areas with insufficient precipitation during the growing season were expanding. Increased winter temperatures and reduced soil freezing contributed to the spread of pests and diseases affecting agricultural crops and forests.

The reduction of forest area altered ecosystems, affected the efficiency of the agricultural sector, and posed risks to food security. Agricultural production was also a source of greenhouse gas emissions and a contributing factor to climate change. R. Murabildayeva *et al.* (2024) have revealed a complex relationship between agriculture, CO_2 emissions, and food security levels. Improving food security directly depended on increasing production, which in turn was accompanied by a rise in CO_2 emissions that pollute the environment and reduce agricultural efficiency. During the period 2000-2022, greenhouse gas emissions in agri-food systems increased by 10%, including farm emissions – by 15%, livestock production accounts for about 54% of these emissions (Martella, 2024). The total greenhouse gas emissions from agri-food systems in 2022 amounted to 16.2 billion tonnes of carbon dioxide equivalent (Gt CO_2-eq) (FAO, 2024b). Industrial food production generated liquid, gaseous, and solid waste that polluted the hydrosphere, atmosphere, and soils. The food industry had the greatest impact on water resources, ranking among the leading sectors in water consumption, and exhibited a low level of wastewater treatment. In terms of water usage per unit of production, the sector held the highest position. Particularly hazardous were solid wastes, which may contain organic substances, including yeast and residues from filtration and clarification processes; bicarbonates obtained during preliminary water treatment; sludge from wastewater treatment facilities; and hazardous wastes such as used oils and solvents generated during equipment maintenance and operation. The most significant negative environmental impacts were caused by the meat, sugar, alcohol, and yeast sectors of the food industry (Ministry of Environmental Protection…, 2021).

One of the evident approaches to enhancing the sustainability of the agricultural sector was the development of organic farming, characterised primarily by the avoidance of synthetic fertilizers and pesticides. In 2022, the agricultural area with certified organic status in Ukraine amounted to 263,619 hectares (OrganicInfo, 2023). The countries with the highest share of organic farming in total agricultural area in 2022 were Austria (26%), Sweden (20%), and Uruguay (19%). 15 of the top 20 countries with the best-developed organic agriculture were located in Europe. In other regions, the balance between conventional and organic farming still leans toward traditional practices (FAO, 2024b). The war initiated by the russian federation in Ukraine has caused significant damage to the functioning of Ukraine's agricultural sector. According to FAO estimates, by the end of 2022, rural households in Ukraine suffered losses of approximately USD 2.25 billion due to the war, of which around USD 1.26 billion were in the crop production sector and USD 0.98 billion in livestock production. About 25% of rural households in Ukraine were unable to continue production, and 38% of them were located in frontline regions (FAO, 2022a). By the end of 2023, 38% of agricultural enterprises were forced to close, and only 45% managed to resume their operations at less than half capacity (Verkhovna Rada of Ukraine, 2023). According to the State Employment Service (n.d.), as of January 1, 2025, 13,813 individuals were registered as unemployed in the agriculture, forestry, and fishing sectors, while 4,386 individuals held the same status in the food processing industry. The supply of job vacancies in the labour market remained low: in agriculture, the number of vacancies was 7 times lower than the number of job seekers, and in food manufacturing, it was nearly twice as low (Table 5).

Table 5. Number of vacancies and job seekers in Ukraine's agri-food sector

Types of economic activity	Code NACE	Number of vacancies, units	Number of job seekers, persons	Number of which registered as unemployed, persons
Agriculture, forestry, and fishing, including:	A	2,027	14,765	13,813
crop and animal production, hunting and related service activities	01	1,881	13,366	12,560
forestry and logging	02	137	1,338	1,201
fishing and aquaculture	03	9	61	52
Manufacture of food products	10	2,616	4,793	4,386
Manufacture of beverages	11	230	306	278
Manufacture of tobacco products	12	0	6	4

Source: State Employment Service (n.d.)

So, military aggression had negatively affected the production volumes of major agricultural crops and had led to the reorientation of farming enterprises toward the cultivation of less resource-intensive crops. In 2023, the lands of the occupied regions were mainly cultivated with wheat, while in government-controlled territories, farmers shifted their focus to growing sunflower and rapeseed, which required fewer resources and have lower production costs compared to cereal crops. In addition, the blockade of Ukraine's Black Sea ports had limited the export opportunities for agricultural products, leading to a decline in their prices on internal markets and significantly reducing the profits of farming enterprises. At the same time, there was a decrease in the production of livestock products and a reduction in the number of livestock (Rusan *et al.*, 2024).

R. Neyter *et al.* (2024) noted that from 2022 to 2025, the total value of destroyed assets in the agricultural sector amounted to USD 10.3 billion. Losses, including foregone income of agricultural producers and increased production costs, have risen to USD 69.8 billion. The environmental disaster caused by the flooding of 5,000 hectares of arable agricultural land due to the actions of the occupiers at the Kakhovka Hydroelectric Power Plant resulted in damages amounting to USD 5.427 million. Disruption of the irrigation system, dependent on the Kakhovka Reservoir, led to annual losses of USD 367.9 million (Koval *et al.*, 2024). Disruptions in food supply chains to food markets have caused a crisis in the functioning of the established system for providing food to the population of Ukraine and the world, leading to increased food prices. This has reduced the level of food security both locally and globally – significantly worsening the physical and economic accessibility of food for low-income groups. From December 2021 to December 2023, food prices increased rapidly, with the largest rises observed in the following groups: bakery products – wheat bread made from first-grade flour (up 37%); meat products – pork (up 56.4%); cereals – millet (up 44%); dairy products – butter (up 46%); and eggs (up 66%). Simultaneously, the purchasing power of the population declined, with the share of food expenses in total household consumption exceeding 52%. In 2023, the average salary in Ukraine amounted to UAH 16,000, which was 8% (or UAH 1,200) higher than in 2022; however, in currency equivalent, the salary decreased by EUR 75 (Ukrinform, 2023).

Also, dairy production was strategically important for every country. In Ukraine, since 1991, the dairy industry had undergone significant transformations due to various challenges and issues, including the COVID-19 pandemic and the war initiated by the russian federation against Ukraine. The decline in the dairy cow population and the shortage of raw milk have caused a localised crisis in the sector. The crisis was further exacerbated by reduced export volumes, loss of markets due to trade embargoes, decreased purchasing power of the population, and the destruction of infrastructure and logistics as a result of military actions. Alongside internal challenges, the global dairy crisis of 2014-2020 also impacted Ukraine by causing a decline in global prices for dairy products. As a consequence, the purchase price of raw milk in Ukraine decreased to USD 22.1 per 100 kg in 2016. Farmers were forced to seek new sources of income and diversify production. Since 2020, prices have risen rapidly due to decreased production and limited physical access for the population during the COVID-19 pandemic (Kozak, 2016). By the end of 2024, the dairy cow population in Ukraine amounted to 1.26 million heads, which was half the number it was in 2014. According to the forecast of the The Union of Dairy Enterprises of Ukraine (n.d.), the number of cows was expected to decline to 1.18-1.14 million heads in 2025-2026, respectively. In 2024, industrial milk production in Ukraine reached 2,809 thousand tonnes, production in farming enterprises – 282.7 thousand tonnes, and household production – 4,620.5 thousand tonnes. Almost all milk produced by household farms was non-graded. The cost of keeping dairy cows continues to rise due to declining profitability of milk production and increasing expenses for feed, diesel fuel, and electricity.

As Ukraine entered the free trade area, the dairy sector was facing new challenges, especially in terms of its competitiveness on the global market. In the cost structure of dairy products, raw milk accounts for 70%, energy resources (electricity, fuel and lubricants) represented another 10%, and the remaining costs included packaging, wages, and enterprise profit. In 2024, the average price range for raw milk (extra, higher, and first grade) was 13.2-14.2 UAH/kg excluding VAT (Chernyshov, 2024). At the same time, according to the Ukrainian Dairy Enterprises Association, the average profitability of dairy farms was 23.1% in 2022 and 26.1% in 2023, with an expected increase to 35% in 2024 (Rodak, 2024). In the second half of 2024, dairy farms increased the price of raw milk by 40%, causing losses to dairy processing plants of nearly UAH 1 billion (Association of Milk Producers, 2025). According to the State Statistics Service of Ukraine (n.d.), the profitability of milk processing and dairy product manufacturing averaged 2.3% in 2022 and 3.0% in 2023. This disparity in profitability between raw milk production and processed dairy products forced processing enterprises to reduce the purchase price of raw milk. Under these conditions, milk producers and processors must work together to seek common solutions for the sustainable development of the dairy value chain and to guarantee fair conditions for both farming and processing operations.

Thus, the study of the retrospective causes and consequences of crisis phenomena indicated the cyclical nature of economic crises and the constant pressure on the food system from economic, political, and other triggers, which led to disruptions in food security in countries worldwide. The vulnerability of food systems had been caused by the economic imbalance between food-importing and food-exporting countries, insufficient food raw materials, and other factors. The consequences of crises for the food system were manifested in rising food prices, a decline in population welfare, low product quality, reduced access to food, profitability disparities, and other related effects. The food sector demonstrated the greatest resilience to crisis phenomena compared to other economic sectors; however, it needed to implement appropriate measures to ensure food security.

Conclusions

The global food crisis may be triggered by wars and conflicts, the negative effects of global warming, soil degradation, neglecting crop rotation, the inability to supply food to countries in need, and accelerated population growth. Economic and military-political instability may lead to a deterioration of food security, especially in needy regions. Risks were exacerbated by changes in global scientific research funding (reduced investments in agrotechnology and increased allocations for military purposes) and by a labour resource crisis. The Ishikawa diagram, developed in the study, showed the cause-and-effect relationships that may lead to a food crisis and provided the basis for the following conclusions. The food crisis cannot be considered a local phenomenon, as it can occur simultaneously in multiple regions, and most of the factors that contribute to it were global in nature. The basic set of food products, whose absence may cause a food crisis, remained small and unchanged (grains, milk, meat) and lacks effective substitutes for a balanced human diet. Droughts, floods, and other climate change-related disasters were becoming more widespread, creating additional threats to the emergence of food crises. In the modern world, a food crisis may arise not from a complete lack of food products, but from their economic inaccessibility, when the purchasing power of the population fails to keep up with rising food prices. Critical manifestations of a food crisis (hunger, malnutrition) in the modern world may occur, when a country's population loses access to food sources. This loss was often caused by artificially created barriers preventing the exchange of personal assets for food. Such artificially induced conditions arose from flawed food policies, which can ultimately lead to catastrophic famine. A strong correlation was identified between food production indicators and GDP, particularly during 2001-2010, when the correlation coefficient for most food products exceeded 0.9. It was found that during the period of active military actions in Ukraine and the COVID-19 pandemic (2020-2024), global food prices increased 2.7-fold, while global wheat stocks decreased by 4.2%. In Ukraine, the area under grain and leguminous crops decreased by 30.5%, whereas the area under sugar beet cultivation increased by 13.6%, and that of energy crops tripled. Future research will focus on forecasting food crises based on an in-depth analysis of adverse factors in specific sectors of the food industry.

Acknowledgements
None.

Funding
None.

Conflict of Interest
None.

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Продовольча криза в сучасному світі: причини виникнення та можливі наслідки для України

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▸ **Анотація.** Запобігання виникненню та ескалації продовольчих криз у кожній країні залежить від своєчасного виявлення їх характерних попереджувальних ознак з метою захисту продовольчої безпеки. Метою дослідження було виявити та узагальнити причини й наслідки продовольчих криз в Україні та у світі для запобігання їх виникненню та пом'якшення негативних наслідків. У дослідженні виявлено специфічні риси системної вразливості продовольчих систем. Обґрунтовано, що багатовимірний і багатовекторний характер одночасних глобальних криз (фінансової, енергетичної, екологічної) створює синергетичну полікризу, складовою якої є продовольча криза. За допомогою діаграми Ішікави було визначено причинно-наслідкові зв'язки, що призводять до продовольчої кризи в Україні, та структуровано причини за основними категоріями. У статті встановлено, що потенційними причинами продовольчої кризи та зниження продовольчої безпеки в Україні можуть бути: невирішені наслідки попередніх криз; глобальна пандемія; прояви світових економічних шоків (зростання світових цін на продовольство, уповільнення зростання сільськогосподарського виробництва, скорочення світових запасів зерна, високі ціни на енергоносії, зростання чисельності населення світу); екологічна криза та екстремальні погодні явища; війни; локальні галузеві кризи, зокрема криза молочної промисловості. У 2020-2024 роках, на тлі пандемії COVID-19 та повномасштабного вторгнення росії в Україну, світові ціни на продовольство зросли у 2,7 рази, тоді як запаси пшениці скоротилися на скоротилися до 272 мільйонів тонн у 2023/2024 маркетинговому році. Результати дослідження показали, що за наявного аграрного, промислового, інноваційного та науково-виробничого потенціалу виникнення критичного голоду в Україні можливе лише за умов штучно створених викликів: війн, що спричиняють руйнування орних земель, захоплення врожаїв, обмеження доступу до продовольства; глобальних техногенних та екологічних катастроф. Теоретичні, методологічні та прикладні положення щодо причин і потенційних наслідків продовольчих криз у сучасному світі можуть слугувати джерелом наукової інформації для розроблення стратегій і програм забезпечення продовольчої безпеки

▸ **Ключові слова:** полікриза; криза голоду; продовольча безпека; синергетичний вплив; продовольче забезпечення; діаграма Ішікави

Received: 30.04.2025. Revised: 29.08.2025. Accepted: 01.10.2025.

EKONOMIKA APK

https://doi.org/10.32317/ekon.apk/5.2025.25

Ekonomika APK, 32(5), 25-36

UDC 636.4:519.86

Economic and mathematical approaches to the organisation of rational feeding of pigs

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▶ **Abstract.** In the context of increasing demands for food security, production efficiency, and sustainable agricultural development, economic and mathematical approaches to organising rational pig feeding were becoming increasingly relevant as tools for making sound management decisions in the livestock sector. The aim of this article was to develop and substantiate economic and mathematical models and methods for optimising the pig feeding process, taking into account the biological needs of animals, the efficient use of feed resources, and the principles of sustainable development in the pig industry. The study used general and specific methods of economic analysis: monographic, analysis and synthesis, dialectical, statistical, and abstract-logical methods. The results presented an overview of pork production in the world and in Ukraine, particularly for the period 2015-2023. A monitoring of pork prices was conducted for January 2023-March 2025. The main directions for the development of feed production and optimisation of pig feeding were outlined to ensure sustainable development of the industry in large-scale, farm, and household operations. The principles for forming an optimised pig diet under high-performance production conditions were identified. Equations for optimising the diet based on nutrient composition and dry matter content were calculated. The permissible ranges of feed ingredients were determined considering pigs' requirements for metabolisable energy, crude and digestible protein, amino acids (lysine, methionine + cystine, tryptophan), crude fiber, dry matter, calcium, and phosphorus. Optimisation of the feeding process made it possible to minimise the cost of the diet. For the grower group of pigs, the following feeding composition was recommended: wheat – 0.5 kg, barley – 0.3 kg, triticale – 0.3 kg, soybean meal – 0.481 kg, and Nutrimin premix – 0.068 kg. It was determined that the cost of the daily diet was UAH 16.09, or UAH 9.76 per 1 kg, and the diet was balanced in terms of nutrients and microelements

▶ **Keywords:** pig farming; balanced diet; optimised feeding; economic analysis model; concentrated feeds

▶ **Suggested Citation**: Voronetska, I., Petrychenko, O., Rossokha, V., & Yurchuk, N. (2025). Economic and mathematical approaches to the organisation of rational feeding of pigs. *Ekonomika APK*, 32(5), 25-36. doi: 10.32317/ekon.apk/5.2025.25.

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Introduction

Rational pig feeding was a key factor in increasing productivity, economic efficiency and rational use of resources in livestock farming. Modern pig farming faced limited resources, unstable pricing policies, rising costs and product quality requirements. Additional risks were created by wars, economic instability and climate change. Livestock farming, in particular pig farming, was a strategic direction for food security, providing the population with high-quality protein products and contributing to the development of the agrarian economy. Scientific substantiation of economic and mathematical approaches to rational pig feeding was an important factor in increasing the efficiency and competitiveness of the industry, ensuring food security and sustainable development of the agro-industrial complex in conditions of limited resources and a changing environment.

The impact of pig farming on the well-being of the population was rather controversial, as it combined both positive and negative factors. Among the positive factors were innovations, the transition to European quality standards and intensification of foreign economic activity. On the other hand, the development of the industry was hampered by environmental risks, health threats, an unfavourable epizootic situation, the dominance of agroholdings and a low level of state support. V. Adamyk *et al.* (2019) emphasised that pig farming was a strategic sector of the agricultural sector, the effectiveness of which depended on innovation, compliance with quality standards, biosecurity and support for small producers, and its development required an integrated approach that combined economic, social and environmental factors to increase the competitiveness and sustainability of the industry. Y. Wang *et al.* (2024) studied the impact of including food waste in animal diets on their performance. The results of the study showed that alternative feed sources have significant potential and opened up opportunities for economic analysis modeling of optimal pig diets, taking into account the efficiency and safety of feeding. This included optimising animal nutrient intake, reducing waste and improving feed quality, while meeting safety standards. M. Balehegn *et al.* (2020) noted that growing demand for animal products in low- and middle-income countries created opportunities for producer welfare and food security, but limited supply and high feed costs constrain livestock development. The authors proposed strategies to improve the supply of quality feed, taking into account biophysical, socio-economic and technological constraints. The study of V. Maksym *et al.* (2022) assessed the economic efficiency of pig farming in Ukraine by modeling the impact of factors such as feed costs, market prices, and scale of production. Profitability in 2020 was 70%, but decreased by 2022 due to increasing feed and energy costs. Optimisation strategies were proposed to increase efficiency and profitability, taking into account market and technological conditions.

Researchers M. Davoudkhani *et al.* (2020) proposed an economic optimisation of pig feeding and transportation strategies taking into account individual biological characteristics of animals. The use of an individual bioeconomic model and an evolutionary algorithm allowed to increase the profitability of production and showed that the integrated optimisation of both strategies is more effective than separate planning. This approach emphasised the importance of economic and mathematical methods for the rational organisation of pig feeding and increasing production efficiency. M.M. Misiura *et al.* (2021) proposed a Bayesian approach to compare models of rational feeding of pigs during the growing and fattening periods. The authors proved that the use of this model contributes to increasing the accuracy of determining the individual nutrient needs of animals, which ensured the optimisation of rations and reduction of feed costs. I. Nesterchuk & O. Yurchenko (2022) emphasised that wartime conditions significantly changed the economic parameters of pig farming in Ukraine, in particular, the structure of production, the level of costs and price dynamics. Such challenges required the use of economic and mathematical approaches to optimise production processes, including the organisation of rational feeding, in order to increase the efficiency and sustainability of the industry.

V. Petrychenko *et al.* (2021) emphasised that the Ukraine had significant potential for the formation of a competitive market for high-protein feeds due to favourable soil and climatic conditions, logistics and developed infrastructure. Scientists emphasised the importance of developing industrial production and organic technologies in the feed sector, as well as improving legislative support in accordance with European standards. I. Verbych & H. Bratkovska (2020) substantiated the usefulness of replacing sunflower meal with soybean feed in the diets of young pigs: animals demonstrated higher average daily gains and better slaughter yield, while feeding efficiency increased due to reduced feed costs per unit of gain. In addition, assessment of the quality of the final product revealed advantages in groups of animals that received soy products, confirming their ability to increase the organoleptic characteristics of the product. K. Pavlova *et al.* (2024) proposed a mathematical modeling that allowed for the least cost-effective formulation of a balanced ration of hay and silage, in accordance with the requirements of the quality and quantity of feed, taking into account the real production process. This model, tested on livestock data in Bulgaria, illustrated the potential of economic and mathematical approaches for optimising balanced feeding, in particular, when forming a pig ration, where the main thing was to minimise feed costs and maximise production efficiency. Scientists K. Syrovatko & V. Vuhliar (2021) substantiated the effect of essential oil supplements on the productivity of young pigs, in particular on the average daily weight gain and nutrient absorption. The results indicated increasing the efficiency of pig breeding and improving the state of the gastrointestinal microflora. The purpose of the research was to develop and scientifically substantiate economic analysis models and methods aimed at optimising the process of feeding pigs, taking into account their biological needs, rational use of feed resources, and ensuring sustainable development of the pig industry.

Materials and methods

The study used both general and special methods of economic analysis, which ensured a comprehensive study of the subject of the research. In particular, the monographic method was used for a deep theoretical analysis of the problem, methods of analysis and synthesis – for establishing relationships between individual economic indicators, the abstract-logical method – for formulating conclusions and generalisations. The information base for the analysis of the state of production in Ukraine of certain types of meat was data from the State Statistics Service of Ukraine (n.d.). The period of 2015-2024 was chosen for the analysis of meat and pork production in Ukraine, since it covered key structural transformations of the industry that occurred under the influence of economic crises, integration processes, and military challenges. Monitoring of pork prices was carried out according to the data of Minfin (2025). The dynamics of pork prices in Ukraine for 2023-2025 was used to provide the economic analysis model with relevant market data in the context of military challenges, price fluctuations, and changes in import dynamics. The source of statistical data on the global development of pig farming in the world was information from the reports of Research and Markets (2025), data from M. Shahbandeh (2025) and the United States Department of Agriculture Foreign Agricultural Service (2025).

The types of feed and their structure in the model were selected based on the recommendations of scientists from the Institute of Feed Research and Agriculture of Podillia of NAAS (Petrychenko & Korniichuk, 2023). The main restrictions in model were the conditions for providing pigs with all the necessary nutrients: metabolisable energy, crude protein, digestible protein, lysine, methionine + cystine, tryptophan, crude fiber, dry matter, calcium, phosphorus. To build an optimisation model, the following notations were introduced:

$$\sum_{j\epsilon N} u_{ij}\, x_j \geq b_i \,(i\epsilon_{Jn}), \tag{1}$$

where i – restriction index, indicating the ordinal number of the feeding element; j – variable index, indicating the ordinal number of the type of feed in the diet; u_{ij} – content of the nutrient element of the i-th type in a unit (1 kg) of the j-th type of feed; x_i – the desired amount of feed of the j-th type included in the diet; b_j – the required amount of the i-th type of nutrient in the diet according to the norm.

To form the ration in the model, the feeding standards for pigs of the grower group were used according to the data from the study of H. Bogdanov *et al.* (2012). The task of optimising a complete mixed ration for feeding pigs of the grower group, included the following parameters: the weight – 30-65 kg; age – 2.5-4.0 months; average daily gain – 750-900 g; type of fattening – meat, type of feeding – concentrate. The diet was optimised by the minimum cost criterion with mandatory compliance with feeding standards, nutrient content and ratio of individual feeds and their groups for a modular pig farm in conditions of the Right Bank Forest-Steppe of Ukraine. The diet was formed based on the results of research by scientists from the Institute of Feed Research and Agriculture of Podillia of NAAS, in particular T. Prudyus *et al.* (2025). The study was conducted in compliance with the requirements ARRIVE (2020).

Results and Discussion

Pork production and the dynamics of the pig industry have a significant impact on ensuring global food security (Maksym *et al.*, 2020). Rational feeding of pigs was a key factor in increasing productivity, economic efficiency and sustainable use of resources in animal husbandry, especially in the context of growing demands for food security, sustainable development and market competition. Limited resources, fluctuations in feed prices and the need to reduce costs made it urgent to implement economic and mathematical approaches to optimise rations taking into account the biological needs of animals, economic parameters of production and changes in the external environment. The pig sector was subject to a large body of EU legislation covering various aspects. Environmental protection, food safety, and public health were addressed by Council Directive No. 98/58/EC (1998), Council Directive No. 2008/120/EC, 2008), and Regulation (EC) No. 178/2002 (2002). Regulations also covered organic production, animal health, and welfare (Commission Recommendation (EU) No. 2016/336, 2016). The European Pigmeat Reflection Group provided further recommendations for the sector (European Commision, 2022), in particular offered strategic guidance to improve sustainability, competitiveness, and welfare in the EU pig sector. However, evidence suggested that EU pig welfare rules were not being sufficiently complied with. The development of animal husbandry provided the population with high-quality products, and the demand for pork was growing, which made the industry attractive to investors. So, the modern economic and mathematical approaches allowed not only to improve the production structure and reduce feed costs, but also to increase the productivity and quality of the final product, in particular by replacing sunflower meal with soy products and optimising the ratios of feed components in rations. This approach emphasised the need for scientifically based formulation of pig rations to maximise efficiency and ensure sustainable development of the industry.

The development of livestock farming largely depended on the creation of a sustainable feed base, which contributed to the increase in livestock population, improving the quality and economic profitability of animal products. Analysis of data for 2020-2024 showed that local producers were becoming a certain guarantee of the state's food security. In addition, their products had the same quality as similar food products from large Ukrainian and European manufacturers (State Statistics Service of Ukraine, n.d.). The primary basis of feed production was the use of highly productive varieties of feed crops adapted to the conditions of different natural and climatic zones of Ukraine. Global trends in natural vegetation change required appropriate breeding developments to adapt perennial and annual grasses to environmental conditions. Ukraine, as one of the world's leading producers and exporters of forage grain crops, legumes, sunflower, soybeans, rapeseed and other valuable raw materials for feed production, had significant untapped potential for the pig breeding industry (Maksym *et al.*, 2022). Researchers T. Soleimani & H. Gilbert (2021) noted that the need of efficiency improvement was the main goal of increasing the sustainability of pig farming from the economic and environmental points of view.

Efficiency of feeds was one of the most important aspects of successful pig farming. Improving pig feeding efficiency will bring three key benefits to pig producers: increase in pig productivity, shortening production cycles and reduced costs. As a result, profitability will increase, waste levels and environmental impact will be reduced, contributing to the sustainable development of the industry (Rooney, 2023). Efficient pork production was becoming a key factor in the profitability of the industry, especially in the context of digital technologies and precision farming. F. Leen *et al.* (2017) emphasised that economic optimisation involved determining the best input-output ratio for maximum profit. In intensive pig production, replacement management played an important role: the terms of the end of fattening period affected the time of putting in operation new batches of piglets and shaped the annual volume of production. Agricultural enterprises having weak competitive rates in pig farming can increase efficiency and strengthen their market positions through technological modernisation, investments in their own processing facilities and sales, development of organic production, and integration with meat processing enterprises and chain stores. Achieving competitiveness was possible through innovative technical re-equipment, cost reduction, mergers with more powerful players, or exit from the market (Samoilyk *et al.*, 2021).

According to the Global Pork Market report, the global pork market was projected to reach 168.5 million tons by 2030, with a 4.1% average annual growth over the period of 2024-2030. In 2024, the global pork market was 132.5 million tons (Research and Markets, 2025). Pig farming was developing in regions with wide access to grain and protein sources. According to the United States Department of Agriculture Foreign Agricultural Service (2025), in 2024 the global pig population exceeded 759 million heads, which was 2.4% less than in 2023. China leads the world in pork production, producing more than the United States and Europe together. China had the largest pig population of any country, with over 430 million heads as of April 2024 (Shahbandeh, 2025). Brazil was the largest pork producer, and Asian countries were the leading pork consumers. Japan, China, Mexico, the United Kingdom, South Korea, the United States, Hong Kong and the Philippines were the largest pork exporters (Kim *et al.*, 2024). Ukraine had the potential to develop pig farming even under martial law. Given modern challenges, it was advisable to create a strategic programme to increase the profitability of the industry based on attracting local and foreign investments to ensure the availability of pork for the population. The opinion of N. Hurzhii *et al.* (2022) about the feasibility of changing the vector of foreign trade by reducing grain exports in favour of pork and allocating an effective export niche for the development of pig farming was supported. Pork production in Ukraine showed a fluctuating trend: after a decrease from 760 thousand tons in 2015 to 697 thousand tons in 2020, there was a partial recovery to 672 thousand tons in 2024, which emphasised its importance for the stability of the meat market. At the same time, beef production had decreased, while poultry meat continued to grow, remaining the main driver of the total volume. The general trend indicated a shift in the production structure towards more productive and profitable types of meat with a gradual recovery of pork volumes (Fig. 1).

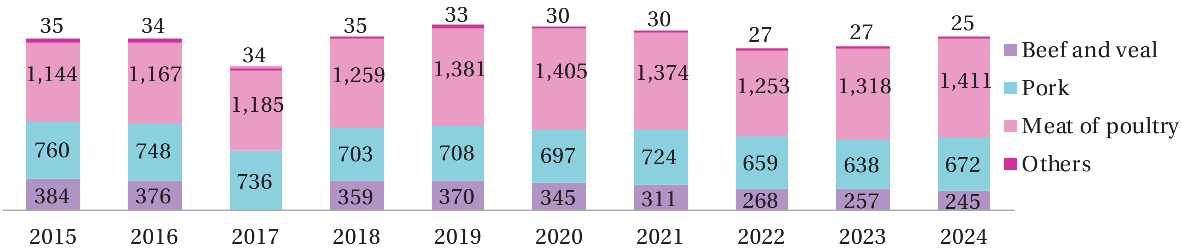

Figure 1. Dynamics of farm animal meat production in Ukraine, 2015-2024 (in slaughter weight, thousand tons)
Source: based on State Statistics Service of Ukraine (n.d.)

The pig industry accounts for about 30% of the supply of Ukrainians with meat products. During 2013-2022, there was a decrease in the number of pig livestock (Fig. 2), in 2023 it amounted to 4948.3 thousand heads, which is 2628.4 thousand heads or 34.7% less than in 2013. The decrease in pig population occurred both in households (by 2239.6 thousand heads, or 55.4%) and in agricultural enterprises (by 764.3 thousand heads, or 19.7%). Pork production in households decreased significantly (by 134.7 thousand tons, or 34.9%).

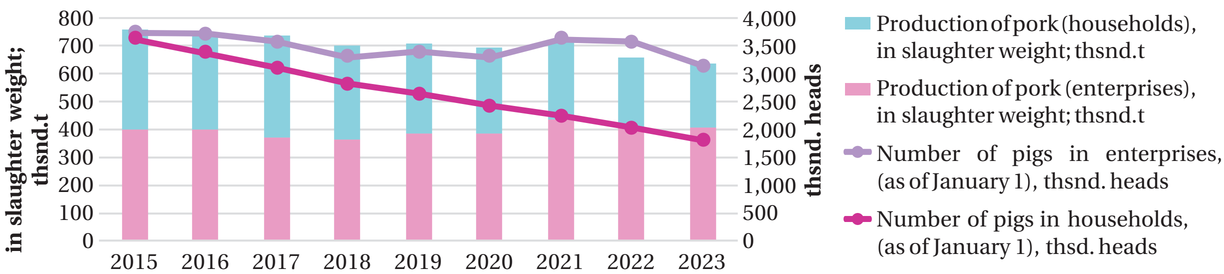

Figure 2. Status and development of pig farming in Ukraine, 2015-2023
Source: based on State Statistics Service of Ukraine (n.d.)

The pig industry in Ukraine was experiencing negative trends. Among the challenges and threats to the industry were: low pig productivity and high costs, rising prices for feeds and feed additives, low feed quality, African swine fever problems in waste and wastewater management, outdated keeping technologies and methods of managing pork production, particularly among small-scale producers. Also, it was an insufficient provision of veterinary standards and biosecurity measures, when keeping pigs, low consumer solvency, considerable competition in the international pork market, logistical problems. Those factors urged agricultural producers to search for ways to increase the efficiency and profitability of pork production. Pork prices in Ukraine showed an unstable, but generally upward trend between January 2023 and March 2025 (Fig. 3). Average retail prices increased from UAH/kg 167.79 in January 2023 to over UAH/kg 190 in February 2025, with minor fluctuations due to seasonality and inflationary factors (Minfin, 2025).

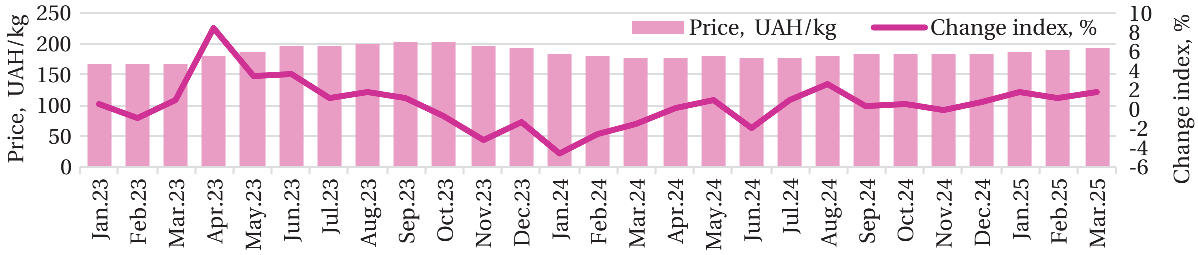

Figure 3. Pork prices in Ukraine monitoring, January 2023-March 2025
Source: based on Minfin (2025)

Purchase prices for live pigs fluctuated within UAH/kg 53-75, with a noticeable drop in mid-2024 due to power outages, mobilisation, and reduced consumer demand. At the same time, a significant increase in purchase prices was recorded by the beginning of 2025, which was associated with expectations of a reduction in livestock, a decrease in imports, and orientation towards the European price level. Overall, pricing in the pork market remained sensitive to external and internal challenges, and the cost of production was an important indicator of food stability. The implementation of the livestock development programme was impossible without the production of sufficient quantities of high-quality, nutritionally balanced feed. According to FAO (2018), one ton of such feed should ensure the production of 0.3 tons of pork. To achieve such indicators, it was necessary to develop the feed production system in large agricultural formations in accordance with their specialisation, using high-protein and energy feeds in pork and poultry meat production. In household feed production it was necessary: to make the most of natural meadows and pastures, to create collective lands of perennial and annual grasses, to cultivate grain and root crops; to use concentrated feeds only in the form of complete, balanced compound feeds and expand the use of premixes; to monitor the quality and safety of feeds, to bring those indicators to the EU requirements.

The main measures to fulfill the tasks set for ensuring the sufficient annual demand for high quality feed, were as follows: optimisation of the structure of sown areas of feed crops in accordance with the specialisation of the farm; development and introduction of the specialised feed crop rotations and concentration of feed production within a radius of 3-5 km from the place of keeping animals; increasing the specific share of high-yielding varieties of perennial leguminous and cereal grasses, annual legumes and soybeans, adapted to different conditions, resistant to pathogens, environmental stresses, having increased symbiotic activity. Also, important measures were an increasing productivity of feed crops through optimising their nutrition and maximising the use of organic fertilizers; using innovative technologies in the procurement and storage of feeds; strengthening control over the quality of feed raw materials; using modern technical means in feed production, which will contribute to labour productivity increase, optimisation of the work terms and improving the quality of feeds. Field feed production was an important component of pig feeding, as it provided access to natural and high-quality feed resources, reduces the cost of purchasing feed on the external market, allowed for the stability of feed supply, regardless of external market fluctuations or supply restrictions, producers can control the quality and safety of the field feed they grow, which allowed obtaining high-quality products. Using homegrown feeds contributed to sustainable production and optimisation of pig diets will ensure efficient use of resources and help to reduce the negative impact of feeding on the environment. In order to optimise pig feeding for sustainable production, 5 main directions should be identified (Fig. 4). The implementation of those directions will contribute to the efficient use of resources, environmental protection and sustainable production of pig products. Ultimate feeding of animals was possible only if the diets contained all nutrients and biologically active substances in optimal quantities and ratios. The basis of pig diets was ensuring their nutritional needs at all stages of the life cycle. Diets can vary significantly depending on the production technology, age of the animals, their physiological needs and type of fattening (Monteiro *et al.*, 2025). Organisation of complete feeding of pigs was the basis for the effective use of feeds that contributed to optimal health, growth and productivity of pigs (Blavi *et al.*, 2021). According to M. Ibatullin (2017), the use of complete compound fed and, accordingly, a decrease in the share of feed per unit of production at the expense of reducing the cost of feed alone will allow reducing the cost of 1 ton of pig weight gain by UAH 1.3-1.5 thousand, in addition to the reduction in cost due to the increased weight gain on condition that total mixed ration was used. Analysis of the reasons, why Ukrainian agricultural producers spent more feed than necessary on the unit of production showed that this negative phenomenon was caused by the unbalanced feeding of pigs. The main cost of the pig diet depended on the price of its filling, thus it was important to reasonably determine the feeding rations. It should be noted that in world practice, when compiling rations for pigs, three indicators of feed energy were used: digestible (DE), metabolisable (OE) and net (NE) one. It was possible to balance rations using any energy indicator, but the chosen model should be uniform. At the same time, in Ukrainian practice, agricultural enterprises producing pig products usually used the metabolisable energy indicator (Ibatullin, 2017). Optimisation of the pig feeding ration was an important component for the ensuring their optimal growth, development and health, including, in particular, scientifically substantiated balance of diets in energy, protein, essential amino acids, vitamins and minerals (Fig. 5).

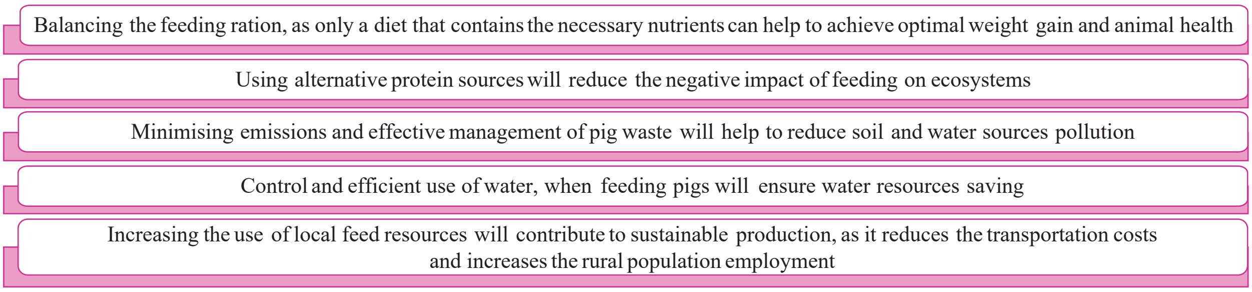

Figure 4. Main directions of optimising pig feeding for sustainable production
Source: developed by the authors

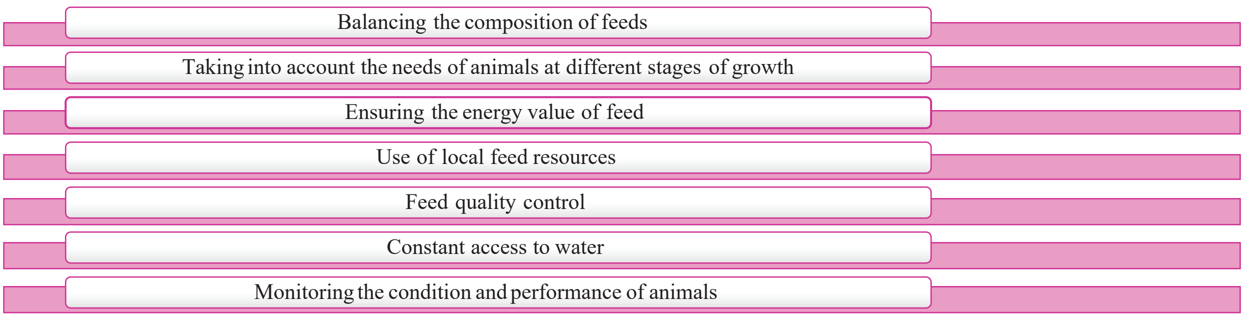

Figure 5. Principles of forming an optimised pig diet in conditions of high-performance production
Source: developed by the authors

The integrated use of those principles and effective use of feeds in pig farming helped to ensure maximal productivity, health and product quality. The implementation of modern research results and innovations in the field of pig feeding can contribute to the improvement of diets and increased productivity. Diet optimisation was a complex task that required consideration of many factors and analysis of the results. A properly balanced and adapted diet can help achieve maximum pig productivity and increase farm efficiency. Rational organisation of pig feeding at different stages of growth was a key factor in production efficiency. The "grower" group deserved special attention, which was characterised by the most intensive weight gain, active development of the skeleton and muscle tissue. It was at this stage that the need for scientifically based optimisation of the diet increases, which involved taking into account technological, economic and resource factors. The use of economic analysis modeling made it possible to form feed programmes with minimal cost without loss of animal productivity. Further detailing of the study of rations required the formalisation of the corresponding parameters in the mathematical model. In accordance with the defined groups of constraints, the designations of the sets *J1*, *J2*, *J3* were introduced, as well as the set of feed types *y* and homogeneous feeds *h*. Such formalisation allowed to isolate the economic content and structure of the model, which provided a scientific basis for optimising rations and forming effective management decisions. In accordance with the nutrient balance, the following restrictions were summarised:

$$\sum_{j\epsilon N} u_{ij}\, x_j \geq bi(i\epsilon J1). \quad (2)$$

According to the dry matter content (kg), it was:

$$\sum_{j\epsilon N} u_{ij}\, x_j \geq bi(i\epsilon J2). \quad (3)$$

According to the feed content in the diet (kg):

$$\sum_{j\epsilon N} u_{ij}\, x_j \geq bi(i\epsilon J3). \quad (4)$$

The objective function was:

$$f(x) = \sum_{j\epsilon N} c_j\, x_j \rightarrow min, \quad (5)$$

where c_j – the cost of a unit of feed of the *j*-th type.

Table 1 showed the feeding rates for pigs of the grower group.

Table 1. Feeding rates for the grower group pigs

Indicators	Values
Metabolisable energy, MJ	13
Crude protein, g	140
Digestible protein, g	109
Lysine	10
Methionine + cystine, g	6
Tryptophan, g	1.7
Crude fiber, g	60
Calcium, g	6
Phosphorus, g	7

Source: based on H. Bogdanov *et al.* (2012)

The model assumed a daily dry matter content in the diet of 1.2-1.5 kg and a mass of individual feed groups within the following limits: wheat grain – from 0.5 kg to 0.84 kg; barley grain – from 0.21 kg to 0.3 kg; triticale grain – from 0.21 kg to 0.3 kg; soybean meal – from 0.35 kg to 0.493 kg; Nutrimin premix – from 0.049 kg to 0.068 kg. Table 2 showed the nutritional value of feeds and their estimated market cost.

Table 2. Nutritional value of a unit of feed and its estimated cost

Indicators	Type of feed, kg				
	Wheat grain	Barley grain	Triticale grain	Soybean meal	Nutrimin premix
Physical quantity of feed, kg	0.5-0.84	0.21-0.3	0.21-0.3	0.35-0.493	0.049-0.068
Metabolisable energy, MJ	14.42	14.57	14.41	15.97	12.2
Crude protein, g	129.5	131.2	113	418	167
Digestible protein, g	95.8	78	85	307	145
Lysine, g	3.9	4.1	4.1	26.3	9.9
Methionine + cystine, g	4.1	3.6	3.6	11.3	3.27
Tryptophan, g	1.3	1.2	1.2	3.7	2.16
Crude fiber, g	21.9	36.9	49	54	5
Calcium, g	0.7	2	2	4.3	35
Phosphorus, g	4.3	3.9	3.9	6.9	5.24
Dry matter, g	850	850	850	900	984
Estimated cost, UAH per 1 kg	5.70	4.50	5.20	12.00	67.00

Source: developed by the author

The system of variables was determined in accordance with the problem statement: x_1 – wheat grain; x_2 – barley grain; x_3 – triticale grain; x_4 – soybean meal; x_5 – Grower pig premix. A system of restrictions has been developed for the first group, which reflected the nutritional requirements for the feeding ration in the amount not less than the norm (Table 3). The second group of restrictions showed the requirements for the dry matter content in the diet (Table 4). The third group of restrictions showed the permissible limits of feed content in the diet (Table 5).

Table 3. Equation of diet optimisation by nutrients (first group of restrictions)

Indicators	Equation
By the metabolisable energy, MJ	$14.42x_1+14.57x_2+14.41x_3+15.97x_4+12.2x_5 \geq 13$
By crude protein content, g	$129.5x_1+131.2x_2+113x_3+418x_4+167x_5 \geq 140$
By digestible protein content, g	$95.8x_1+78x_2+85x_3+307x_5+145x_5 \geq 109$
By lysine content, g	$3.9x_1+4.1x_2+4.1x_3+26.3x_5+9.9x_5 \geq 10$
By the content of “methionine + cystine”, g	$4.1x_1+3.6x_2+3.6x_3+11.3x_5+3.27x_5 \geq 6$
By tryptophan content, g	$1.3x_1+1.2x_2+1.2x_3+3.7x_5+2.16x_5 \geq 1.7$
By the crude fiber content, g	$21.9x_1+36.9x_2+49x_3+54x_5+5x_5 \geq 60$
By calcium content, g	$0.7x_1+2x_2+2x_3+4.3x_5+35x_5 \geq 6$
By phosphorus content, g	$4.3x_1+3.9x_2+3.9x_3+6.9x_5+5.24x_5 \geq 7$

Source: developed by the author

Table 4. Equation for the diet restrictions by the dry matter content (second group of restrictions)

Restriction	Equation
Not less than	$0.85x_1+0.85x_2+0.85x_3+0.9x_5+0.984x_5\geq 1.2$
Not more than	$0.85x_1+0.85x_2+0.85x_3+0.9x_5+0.984x_5\leq 1.5$

Source: developed by the author

Table 5. Permissible limits of feed content in the diet (third group of restrictions), kg

Indicators	Not less than	Not more than
Wheat grain	$x_1\geq 0.5$	$x_1\leq 0.84$
Barley grain	$x_2\geq 0.21$	$x_2\leq 0.3$
Triticale grain	$x_3\geq 0.21$	$x_3\leq 0.3$
Soybean meal	$x_4\geq 0.35$	$x_4\leq 0.49$
Nutrimin premix	$x_5\geq 0.049$	$x_5\leq 0.068$
Equation	$0.85x_1+0.85x_2+0.85x_3+0.9x_5+0.984x_5\geq 1.2$	$0.85x_1+0.85x_2+0.85x_3+0.9x_5+0.984x_5\leq 1.5$

Source: developed by the authors

Taking into consideration that the minimum cost of the ration was chosen as the optimality criterion, then the objective function, minimum cost of the ration (UAH) will be as follows:

$$F=6.3x_1+4.2x_2+6.3x_3+9.5x_4+67x_5\rightarrow min. \quad (6)$$

According to the optimal plan, the following feed should be included in the daily ration for the fattening pigs of the grower group: wheat grain – 0.5 kg; barley grain – 0.3 kg; triticale grain – 0.3 kg; soybean meal – 0.481 kg; Nutrimin premix – 0.068 kg (Table 6).

Table 6. Results of solving the economic and mathematical problem of optimising the daily ration for fattening pigs of the grower group

Limitation number	Variables	Types of feeds					Restriction		
	Name of limitations	Wheat grain	Barley grain	Triticale grain	Soybean meal	Nutrimin premix	Left side	Sign	Right side
		x_1	x_2	x_3	x_4	x_5			
	Variable values, kg	0.500	0.300	0.300	0.481	0.068			
I. Nutrient balance									
1	Metabolic energy, MJ	14.42	14.57	14.41	15.97	12.2	24.421	≥	13
2	Crude protein, g	129.5	131.2	113	418	167	350.589	≥	140
3	Digestible protein, g	95.8	78	85	307	145	254.448	≥	109
4	Lysine, g	3.9	4.1	4.1	26.3	9.9	17.744	≥	10
5	Methionine + cystine, g	4.1	3.6	3.6	11.3	3.27	9.872	≥	6
6	Tryptophan, g	1.3	1.2	1.2	3.7	2.16	3.298	≥	1.7
7	Crude fibre, g	21.9	36.9	49	54	5	63.055	≥	60
8	Calcium, g	0.7	2	2	4.3	35	6.000	≥	6
9	Phosphorus, g	4.3	3.9	3.9	6.9	5.24	8.168	≥	7
II. Dry matter content, kg									
10	min	0.850	0.850	0.850	0.900	0.984	1.435	≥	1.2
11	max	0.850	0.850	0.850	0.900	0.984	1.435	≤	1.5
III. Feed content in the diet, kg									
12	Wheat grains min	1					0.500	≥	0.5
13	Wheat grains max	1					0.500	≤	0.84
14	Barley grains min		1				0.300	≥	0.21
15	Barley grains max		1				0.300	≤	0.3
16	Triticale grains min			1			0.300	≥	0.21
17	Triticale grains max			1			0.300	≤	0.3
18	Soybean cake min				1		0.481	≥	0.35
19	Soybean cake max				1		0.481	≤	0.49
20	Nutrimin min premix					1	0.068	≥	0.049
21	Nutrimin max premix					1	0.068	≤	0.068
	Minimum cost of the ration, UAH	**5.70**	**4.50**	**5.20**	**12.00**	**67.00**		**min**	**16.09**

Source: developed by the authors

According to the results of verification of the conditions fulfillment, the following was established: the 1st group of restrictions – the need for calcium is met at a minimum; the content of metabolisable energy, crude protein, digestible protein, lysine, methionine + cystine, tryptophan, crude fiber, phosphorus was above the minimum requirement; the 2nd group – the amount of dry matter exceeded the minimum required rate; the 3rd group – the amount of feed was within the recommended values. Objective function: with such composition of the diet, the minimum cost of the daily ration will be UAH 16.09, the cost per 1 kg of feed – UAH 9.76. The resulting diet was balanced in terms of nutrients and trace elements.

So, it was worth to noting that scientists B.M. Ali *et al.* (2018) proposed a stochastic bioeconomic model of pig farming to assess the impact of innovations in feeding on economic performance and environmental parameters of production. The results of their work confirmed the feasibility of using local by-products in pig rations, which ensured cost reduction, improved management decisions and increased profitability of the industry. Thus, an integrated approach to organising feeding opened up new opportunities for increasing the competitiveness of pig farming in Ukraine. An important confirmation was the results of the study by K.P. Pawłowski *et al.* (2025), which proved the effectiveness of economic analysis modeling in combining pig productivity with environmental responsibility of production. This approach created a methodological basis for further formalisation of parameters and optimisation of feeding programmes.

According to T. Prudyus *et al.* (2025), the rational use of feed additives activated natural and adaptive factors of the body's defenses in sows and piglets, allowing to increase the resistance and productivity of livestock. This created a scientific basis for economic and mathematical modeling of diets that took into account the biological needs of animals, the effective use of local feed resources and the principles of sustainable development of the industry, while ensuring a reduction in losses and an increase in production efficiency. The use of economic analysis models in this context made it possible not only to optimise diets according to the criteria of nutritional value and the cost of concentrated feeds, but also to integrate the results into a broader analysis of the economic efficiency of production. V. Orel & M. Korniietskyi (2021) believed that this approach allowed to assess the impact of feed costs on the cost and profitability of pig farming, taking into account the scale of production, investment, and logistics, which, in turn, contributed to the formation of scientifically sound strategies to increase the competitiveness of the industry.

The development and use of economic and mathematical models of operational forecasting provided the ability to determine the optimal parameters of rational pig feeding, outline the limits of investment risks, and select the most effective production options, taking into account the need and cost of concentrated feed, water, and energy sources (Pidtereba, 2022). The proposed economic analysis model allowed to form a balanced diet for pigs with the optimal inclusion of concentrated feeds, which ensured full satisfaction of the animals' needs for nutrients and minimised the cost of daily rations. The proposed approach demonstrated the effectiveness of integrating economic and biological parameters in the process of organising rational feeding, contributing to increasing productivity and economic feasibility of pig production.

▸Conclusions

In Ukraine, meat production was growing mainly due to poultry, while pork and beef volumes were decreasing, which indicated imbalances in the structure of the meat market. Live pork prices remain sensitive to external and internal factors, which emphasised the need to optimise production. The use of economic and mathematical approaches to organising rational pig feeding allowed for increased resource efficiency, reduced production costs, and improved stability and competitiveness of the industry. Modeling of the optimised diet for the pig fattening group showed that balanced feeding, taking into account the needs for protein, amino acids, energy, and macronutrients, allowed for a minimum daily ration cost of UAH 16.09, and the cost of 1 kg of feed was UAH 9.76. At the same time, all mandatory restrictions on the content of nutrients, dry matter, and the amount of feed in the diet were met. Such results confirmed the effectiveness of the economic and mathematical approach, focused on minimising costs while maintaining high productivity indicators.

The competitiveness of Ukrainian pig farming largely depends on effective rational feeding and the development of its own feed base. The use of cereals, legumes and oilseeds required adaptation to climate change and modern technologies for harvesting and storage. Economic analysis modeling showed that optimising the structure and cost of feed increases pig productivity, reduces costs and strengthens food security. The limitations of the study were related to the incompleteness of input data, the variability of biological and economic parameters, the dynamism of the market environment, methodological simplifications of models, insufficient digitalisation of production, and the influence of socio-economic factors that complicated the practical application of the results obtained. Further research should focus on price forecasting, the impact of climatic factors and the integration of alternative protein resources, which will contribute to the sustainable development of the industry and reduce its environmental impact.

▸Acknowledgements

None.

▸Conflict of Interest

None.

▸Funding

None.

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Економіко-математичні підходи до організації раціональної годівлі свиней

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▸ **Анотація.** В умовах зростаючих вимог до продовольчої безпеки, ефективності виробництва та сталого розвитку сільського господарства, економіко-математичні підходи до організації раціональної годівлі свиней набули актуальності як інструмент для прийняття обґрунтованих управлінських рішень у галузі тваринництва. Метою статті була розробка та обґрунтування економіко-математичних моделей і методів оптимізації процесу годівлі свиней з урахуванням біологічних потреб тварин, ефективного використання кормових ресурсів та принципів сталого розвитку свинарської галузі. У дослідженні використано загальні та спеціальні методи економічного аналізу: монографічний, аналізу і синтезу, діалектичний, статистичний та абстрактно-логічний. У результатах дослідження висвітлено стан виробництва свинини у світі та Україні, зокрема, за 2015-2023 роки. Розглянуто моніторинг цін на свинину за період січень 2023-березень 2025 року. Окреслено основні напрямки розвитку кормовиробництва й оптимізації годівлі свиней для забезпечення сталого розвитку галузі в великотоварних та фермерських господарствах, господарствах населення. Визначено принципи формування оптимізованого раціону свиней в умовах високопродуктивного виробництва. Розраховано рівняння оптимізації раціону за поживними речовинами та вмістом сухої речовини. Визначено допустимі межі кормових інгредієнтів з урахуванням потреб свиней в обмінній енергії, сирому та перетравному протеїні, амінокислотах (лізин, метіонін + цистин, триптофан), сирій клітковині, сухій речовині, кальції та фосфорі. Оптимізація процесу годівлі дозволила мінімізувати вартість раціону. У дослідженні, для годівлі свиней групи гровер було рекомендовано використовувати: пшеницю – 0,5 кг, ячмінь – 0,3 кг, тритикале – 0,3 кг, соєву макуху – 0,481 кг, премікс Нутрімін – 0,068 кг. Було визначено, що вартість добового раціону становила 16,09 грн, або 9,76 грн за 1 кг, також раціон був збалансований за поживними речовинами та мікроелементами

▸ **Ключові слова:** свинарство; збалансований раціон; оптимізована годівля; модель економічного аналізу; концентровані корми

Received: 14.05.2025. Revised: 01.09.2025. Accepted: 01.10.2025.

EKONOMIKA APK

https://doi.org/10.32317/ekon.apk/5.2025.37
Ekonomika APK, 32(5), 37-47

UDC 631.1-330.3

Material and technical base of agribusiness in EU countries and Ukraine

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▶ **Abstract.** The aim of this article was to assess the availability of basic means of production in Ukrainian agriculture, their use and renewal in comparison with EU countries, as well as to establish the impact of the technological level of the agricultural sector on its efficiency. The study was conducted on the basis of official statistical data from the United Nations. A comparative assessment of the modern level of provision of fixed assets in the agricultural sector of European countries and Ukraine was carried out. It was established that increasing the technological level of agricultural production ensured growth in added value in the country's agriculture, the level of labour productivity, its efficiency and a reduction in the number of employees. Analytical studies were conducted on the dynamics and effectiveness of investing fixed capital in the agricultural sector of European countries with different levels of material and technical support. It has been established that the indicators of provision and formation of fixed capital of Ukrainian agricultural enterprises, labour productivity and added value in agriculture in Ukraine were the lowest in the European space, which was a consequence of the low level of investment opportunities of farms and led to a deepening of the technical and technological backwardness of the industry and threatens the food security of Ukraine. It was determined one of the main factors determining the quantity and quality of agricultural products and the efficiency of Ukraine's agribusiness sector was the level of material and technical resources and their innovative development. The expanded reproduction, renewal and modernisation of the technical and technological support of Ukraine's agricultural production required the state to play an active role in shaping institutional and economic conditions

▶ **Keywords:** agriculture; fixed assets; fixed capital; technical re-equipment; real investments

▶ Introduction

Leading European countries are improving their positions in Ukrainian and global food markets by implementing the concept of sustainable development and transitioning to high-tech agricultural support, as the level of material

▶ **Suggested Citation**: Adamchuk, V., Perepelytsia, N., & Hrytsyshyn, M. (2025). Material and technical base of agribusiness in EU countries and Ukraine. *Ekonomika APK*, 32(5), 37-47. doi: 10.32317/ekon.apk/5.2025.37.

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and technical support for agriculture is a key factor in its competitiveness and profitability. The development of the material and technical base of agricultural enterprises is determined by the growth in the level of provision of their basic means of production. The volume and dynamics of growth in agricultural production, as well as its profitability, depend on the completeness of technical resources and their effective use.

Researcher Yu. Lipsky (2024) explored the reproduction and renewal of the material and technical base (MTB) of agricultural enterprises. The author noted that its structure and quality depend on a comprehensive assessment of land as both a means and an object of labour-considering natural and climatic conditions, land use, and soil characteristics. These factors influenced enterprise specialisation, production costs, and the choice of machinery, technology, and resources. The interrelation between land properties and technical resources determined not only the composition of an enterprise's material base, but also soil fertility, which depended on compliance with scientific technologies, the level of biologisation, and technological innovation. The problems of forming and renewing the fixed assets of the Ukrainian agricultural business were considered by V. Kopytko & O. Kopytko (2021), who noted that the use of intensive approaches to the reproduction of material and technical resources leads to an increase in production volumes and, most importantly, improves its quality characteristics. However, unlike leading countries, the agricultural sector in Ukraine was dominated by extensive methods of technical base reproduction, caused by price disparities between agricultural and industrial products. According to the authors, it was is disparity that was the key factor limiting farmers' ability to purchase the necessary material and technical resources, and therefore, the main task of the state in the field of price regulation should be to provide agricultural enterprises with a sufficient level of income for expanded reproduction. The calculation of the normative demand for fixed assets in agriculture for the production of agricultural products for the period up to 2025, which was carried out by a team of scientists led by O. Zakharchuk *et al.* (2024), shows that the modern value of fixed capital was 4.8 times less than the scientifically justified requirement, which was caused by the insufficiency of domestic agribusiness's own investment resources to ensure the model of expanded reproduction of fixed production assets. The researchers noted that one of the reasons for this situation was the underestimation of fixed assets in the agricultural sector, which led to an artificial overstatement of agricultural performance indicators. Another factor slowing down the pace of renewal of the machine and tractor fleet of agricultural enterprises was the high cost of foreign equipment and the degradation of domestic agricultural machinery manufacturing.

The need to increase investment in the fixed capital of agricultural producers was justified in the research of Yu. Voloshchuk (2018). The author drew attention to the insignificant renewal of the machine and tractor fleet with new generation equipment and the negative trends in the reduction of the total number of technical means in use by agricultural enterprises. In the author's opinion, the share of capital investments in the agricultural sector in the sectoral structure of Ukraine's economy should be at least equal to the share of agriculture in the gross value added of the state. The author also emphasised that in order to implement the model of expanded reproduction of the fixed assets of agricultural enterprises, it was necessary to ensure that the volume of acquisition and modernisation of fixed assets exceeded the volume of their disposal and write-off by more than 1.5 times. Innovative production technologies and technical means used for their implementation determined the level of progressiveness of the technological structure of agricultural production. The theoretical and methodological foundations for the qualitative assessment of technical means with the aim of obtaining objective information about their operational characteristics and the effectiveness of using innovative technologies in the agricultural sector were developed by O. Vyshnevetska (2024).

However, Ukraine's agricultural production was effectively deprived of the tools to solve financial problems in order to improve the material and technical base and increase capital investments, according to T. Shutko (2024). The author's analytical research confirmed that since 2018, capital investments in the agricultural sector of the Ukrainian economy have been steadily declining, which deepened its technological backwardness. The introduction of smart farming technologies has enabled modern agricultural enterprises in Denmark, Germany, Sweden and other leading countries to optimise their production costs and increase the productivity and profitability of their agribusinesses. These farms were models of highly intensive production of the sixth technological paradigm. Ukraine's strategic goal was accession the European Union, so the integration of the Ukrainian agricultural sector into the European market space required a comprehensive study of competitive conditions, identification of the main factors for increasing profitability and ensuring the sustainability of agricultural production in the context of economic globalisation. The need for expanded reproduction of the material and technical support of Ukraine's agricultural sector as an important factor in its competitiveness and the problems of investment activity of agricultural enterprises have been substantiated by researchers, but a number of aspects have remained outside the scope of comprehensive analysis, which emphasised the need for further research on this topic. The aim of this study was to assess the availability of basic fixed production assets in Ukrainian agriculture, their use and renewal in comparison with EU countries, and to determine the impact of the technological level of the agricultural sector on its efficiency. The objectives of research were to identify the factors of efficiency of Ukrainian agribusiness, reveal the shortcomings of the system of reproduction of the main means of agriculture, and develop proposals for optimising state policy to stimulate the renewal of technical support for agricultural enterprises on an innovative basis.

▸ Materials and methods

The work applied the dialectical method of scientific cognition, as well as both general scientific and specific research methods. In particular, economic and statistical methods (comparative analysis, average and relative values, index analysis, tabular and graphical methods) were used in analytical studies to assess the state, dynamics and trends in the development of fixed assets in agriculture. System analysis was used to identify factors affecting the efficiency of updating fixed assets in the agricultural sector. Using abstract-logical and generalisation methods, conclusions were formulated and priority areas of regulatory state policy were identified to stimulate the expanded reproduction of fixed capital in the agricultural sector.

The information base of the study was based on scientific publications on the formation, use and renewal of fixed assets in agriculture, official statistical data from the Food and Agriculture Organisation of the United Nations (FAO) from 2000 to 2021, information from electronic resources, and the results of the authors' own calculations (FAOSTAT, 2023). The chronological scope of the analysis was limited to 2021 to ensure the most objective assessment of the potential of Ukraine's agricultural sector and its development trends, without taking into account the negative impact of the war on economic processes. To assess the technological level of the agricultural sector, the methodological approaches from FAOSTAT (2023) were used. Specifically, the ratio of the added value of agricultural products to the value of agribusiness fixed assets was determined, which showed, how many units of added value are generated from each unit of fixed capital invested. In high-income countries, this indicator was below 0.5, which meant that their agricultural production was largely high-tech and mechanised. In many low- and lower-middle-income countries, this indicator exceeded one, indicating a less capital-intensive agricultural sector.

The collection of statistical information and the formation of a database included the following indicators: the value of fixed assets in agriculture in actual and comparative prices; the size of agricultural land; the level of employment in agriculture; the value of gross output in actual prices; the added value of agriculture in comparative prices; the value of real investments (gross fixed capital formation) in agriculture in comparative prices. In total, indicators from 12 European countries (Bulgaria, Denmark, Spain, Italy, Netherlands, Germany, Poland, Romania, Hungary, France, Sweden, Switzerland) and Ukraine were analysed. A comparative analysis of the availability of fixed assets for agricultural production was carried out using indicators of capital-labour ratio and capital-labour intensity. For the analytical study of the efficiency of the use of fixed assets in agribusiness, indicators of labour productivity, return on assets and capital intensity were used. The pace of technical re-equipment of production was assessed by the level of real investment in the fixed capital of agricultural enterprises, and the efficiency of fixed asset renewal was reflected in the dynamics of the added value of agricultural products. The dynamics of the indices of employment in the agricultural sector, the level of real investment, capital intensity of labour and added value of agriculture compared to 2000 were presented graphically for eight countries.

▸ Results and Discussion

In the source Eurostat (2024) was noted that over almost a decade – from 2015 to 2024 – labour productivity in agriculture in the European Union countries increased by 37.2%. Real factor income relative to production costs increased by 11%, while labour costs in the agricultural sector decreased by 19.1%. In other words, Europe is addressing the issue of food security by steadily increasing agricultural production with less use of labour and production resources through the introduction of sustainable production technologies based on automated and robotic technical means and systems. Researcher I. Dvornyk (2021) analysed the dynamics of labour productivity per employed worker in Ukrainian agriculture and found that it grew by 48.81% in 2015-2019, specifically by 44.61% in crop production and in animal husbandry – by 61.78%. At the same time, the current level of labour productivity in Ukrainian agricultural production indicates that the available resource potential is not being fully utilised and does not meet the modern requirements for the development of agribusiness.

The low level of labour productivity in Ukraine's agricultural production is a consequence of the mismatch between the level of technical equipment of agricultural producers and the requirements of innovative development of the industry. To establish the level of provision of the agricultural sector with means of production, the efficiency of their use and renewal, the indicators of the European Union countries and Ukraine were studied based on open statistical data from the FAOSTAT (2023) (Table 1).

Table 1. Provision of basic agricultural assets in European countries (2021)

Country	Fixed assets of the AIC, mln USD	Area of agricultural land, thsd ha	Employment in agriculture, thsd people	Capital provision, thsd USD/ha	Capital-labour ratio, thsd USD/person
Bulgaria	7,365	5,046	195.1	1.46	37.75
Denmark	40,335	2,618	59.4	15.41	679.04
Spain	81,454	26,228	810.2	3.11	100.54
Italy	185,784	12,403	921.2	14.98	201.68
Netherlands	72,620	1,812	207.5	40.08	349.98
Germany	204,970	18,240	524.2	11.24	391.01
Poland	23,291	14,719	1,525.5	1.58	15.27
Romania	45,501	13,079	1,445.2	3.48	31.48
Hungary	31,525	5,049	207.4	6.24	152.00
Ukraine	31,783	41,892	2,744.9	0.76	11.58
France	136,510	28,554	703.8	4.78	193.96
Sweden	57,842	1,529	102.0	18.47	567.08
Switzerland	55,358	3,003	112.0	36.21	494.27

Source: based on FAOSTAT (2023)

According to FAOSTAT (2023), Ukrainian farmers' access to basic resources amounted to USD 759 per 1 hectare of agricultural land. For comparison, in Poland and Bulgaria, this figure was twice as high, in Italy, Sweden and Denmark, it exceeded the Ukrainian figure by almost 20 times, and in the Netherlands, by more than 50 times. While in Germany there are 90 tractors per thousand hectares of agricultural land, in Ukraine there are only ten, most of which are morally and physically worn out. Given the experience of neighbouring countries and the prospects for Ukraine's integration into the European community, it is important to develop competitive advantages for Ukrainian agricultural products on global food markets. Significant factors in increasing competitiveness in the global food market include: improving product quality through greening production; systematic modernisation of the agricultural sector, automation and robotisation of technological processes, introduction of innovative resource-saving and soil-protecting technologies, and development of deep processing of products. Ukraine is already taking certain steps in this direction: in 2010-2021, gross agricultural production increased from USD 28.3 to 51.4 billion, catching up with Germany, Italy and Spain, where average gross production volumes remained stable. However, the results of the analysis of the efficiency of agricultural production in terms of labour productivity and land use as the main means of production show significant untapped potential in the Ukrainian agricultural sector.

As shown in Table 2, in 2021, gross output per hectare of agricultural land in Ukraine amounted to USD 1,226.1, while in Germany this figure reached USD 2,888.7, in Spain – USD 2,172.4, and in Italy – USD 4,267.3. The Netherlands achieved the highest level of land use efficiency in Europe – USD 10,320.3 per hectare, which exceeds the Ukrainian level by more than 8 times.

Table 2. Efficiency of use of fixed assets in agricultural production in European countries (2021)

Country	Total gross agricultural output, mln USD	Gross output production per 1 ha of agricultural land, thsd USD	Labour productivity, thsd USD/person	Capital output ratio	Capital intensity
Bulgaria	5,851.4	1,159.6	29.99	0.79	1.26
Denmark	9,901.1	3,781.9	166.69	0.25	4.07
Spain	56,978.8	2,172.4	70.33	0.70	1.43
Italy	52,927.3	4,267.3	57.45	0.28	3.51
Netherlands	18,700.4	10,320.3	90.12	0.26	3.88
Germany	52,689.1	2,888.7	100.51	0.26	3.89
Poland	29,315.8	1,991.7	19.22	1.26	0.79
Romania	19,334.5	1,478.3	13.38	0.42	2.35
Hungary	8,240.8	1,632.2	39.73	0.26	3.83
Ukraine	51,365.4	1,226.1	18.71	1.62	0.62
France	83,837	2,936.1	119.12	0.61	1.63
Sweden	8,174.1	1,517.3	46.58	0.08	12.18
Switzerland	4,750.8	5,346.0	72.98	0.15	6.77

Source: based on FAOSTAT (2023)

Labour productivity, measured by the value of gross output per employee, in Ukraine's agricultural sector is USD 18,710 per employee, which is 5.4 times less than in Germany, 3.8 times less than in Spain, in Italy – 3 times, and in the Netherlands – 4.8 times. Denmark and France demonstrate the highest labour productivity indicators – USD 166.7 thousand and USD 119.1 thousand, respectively. Labour productivity is a key indicator reflecting the level of development of agriculture and the technological structure of its production systems, and the level of labour productivity directly correlates with its capital intensity. Interestingly, Ukraine has the best indicators of capital intensity and return on capital among European countries, despite its lower level of material and technical support. This once again emphasises the priority of technical and technological modernisation of the Ukrainian agricultural sector in the context of economic globalisation.

The technical re-equipment of agricultural production requires significant capital investments in material and technical resources, primarily in modern technology, which is a determining factor in the competitiveness of products and the final productivity of production (Mykhaylov, 2018). The technological modernisation of agriculture increasingly relies on renewable energy and resource-efficient technologies. Recent studies confirm the effectiveness of integrating solar energy systems into agricultural processes. For instance, O. Sadovoy *et al.* (2024) demonstrated the optimisation of solar power plants for sprinkler irrigation systems in southern Ukraine, which can significantly reduce energy dependence and operational costs in crop production. According to estimates by Ukrainian economists, the modern level of material and technical support for agribusiness in Ukraine is about one-third of the normative requirement and directly depends on the investment potential of a particular farm. The gross accumulation of fixed capital in the agricultural sector directly depends on the inflow of real investments into the agro-industrial complex. As can be seen from Table 3, in 2021, they amounted to USD 2,642.2 million in Ukraine, which is more than in Bulgaria, Hungary, Denmark, and Sweden. At the same time, only USD 963 of investment per employee in Ukrainian agriculture was accounted for, while in Bulgaria this figure was USD 3,756, in Hungary – 8,207, in Poland – 3,288. Sweden, Germany, France, Denmark, the Netherlands and Switzerland invested more than USD 20,000 per employee in the technological development of the agricultural sector, exceeding the amount of investment in Ukraine by 21 to 33 times.

Table 3. Efficiency of fixed capital investment in the agricultural sector of European countries (2021)

Country	Investments in fixed capital, mln USD	Real investments per agricultural worker, thsd USD	Real investments per 1 ha of agricultural land, thsd USD	Added value of agricultural production, mln USD	Added value per agricultural worker, thsd USD	Capital output ratio of agricultural added value
Bulgaria	732.8	3.756	728	3,671	18.82	0.50
Denmark	1,627	27.391	1,688	4,418	74.38	0.11
Spain	7,560.1	9.331	1,505	39,478	48.73	0.48
Italy	12,648.1	13.730	3,300	40,926	44.43	0.22
Netherlands	5,639.3	27.177	8,620	15,619	75.27	0.22
Germany	12,119.5	23.120	1,670	30,460	58.11	0.15
Poland	5,016.4	3.288	1,038	15,275	10.01	0.66
Romania	2,684.7	1.858	1,041	13,612	9.42	0.30
Hungary	1,702.1	8.207	1,257	6,349	30.61	0.20
Ukraine	2,642.2	0.963	519	21,746	7.92	0.68
France	15,262.1	21.685	1,676	47,860	68.00	0.35
Switzerland	3,547.9	31.678	1,695	5,091	45.46	0.09
Sweden	2,096.6	20.555	5,389	8,240	80.78	0.14

Source: based on FAOSTAT (2023)

The distribution of investments in 2021 per unit of agricultural land in European countries is also the lowest for Ukraine – USD 519 per 1 hectare. Among the European Union countries under consideration, the smallest investments per hectare of land use were in Bulgaria and Poland – USD 728 and USD 1,038, respectively. Most countries invest between USD 1,300 and USD 1,700 per hectare. The Netherlands, with investments of USD 8,620 per hectare, occupies the leading position. According to the methodology for assessing the technological level of the industry used in international statistics, the level of technical and technological support for agricultural production is determined by the ratio of the added value of agricultural products to the value of fixed assets in agribusiness (hereinafter referred to as the return on added value), which shows how many units of added value are obtained in agriculture from each unit of fixed capital invested. In high-income countries, this indicator is below 0.5, which means that their agricultural production is largely high-tech and mechanised. In many low- and lower-middle-income countries, this indicator exceeds one, indicating a less capital-intensive agricultural sector.

Denmark, Sweden and Germany have developed agricultural production facilities, which confirms the level of return on added value of their agriculture, which is 0.11, 0.14 and 0.15, respectively. In contrast, Ukraine, Poland and Bulgaria are countries with a low technological level of production processes and a significant share of manual labour in agribusiness, and each unit of fixed capital invested ultimately yields 0.5 to 0.68 units of value added. Added value, also known as the sum of factor incomes, is formed in the production process from three components: the result (income) from the use of labour, land and fixed capital. It is calculated as the difference between the market price of gross output and the cost of purchased resources (seeds, fuel, fertilisers, plant protection products, feed) and services used in production. Added value includes wages, depreciation, profit, rent, taxes. The higher the added value, the higher the investment opportunities and profits. The analysis showed that Ukraine has the lowest level of added value in agriculture per employee, at 7.92 thousand US dollars. For comparison, this indicator is 58.11 in Germany, 74.38 in Denmark, and 80.78 in Sweden. This means that Ukrainian farmers have up to 10 times less internal investment resources for modernisation and development of production.

Income from the use of labour is directly correlated with income from the use of fixed assets. The capital-labour ratio of Ukrainian farmers is the lowest in Europe, so the growth in added value in agriculture in Ukraine over the last 20 years has been achieved exclusively through the intensification of land use. In fact, Ukrainian agricultural producers have taken a kind of "loan" from future generations by depleting soil fertility in order to maintain the competitiveness of their products on global markets. Ukrainian agricultural producers still do not take into account the removal of nutrients and microelements from the soil that are used to form the harvest. The above conclusion is confirmed by an analysis of the dynamics of such indicators of the efficiency of fixed assets as the indices of changes in the number of agricultural workers, their capital-labour ratio, the added value they produce, and the amount of investment in the material and technical re-equipment of the agricultural sector in comparative prices for 2015 (Fig. 1).

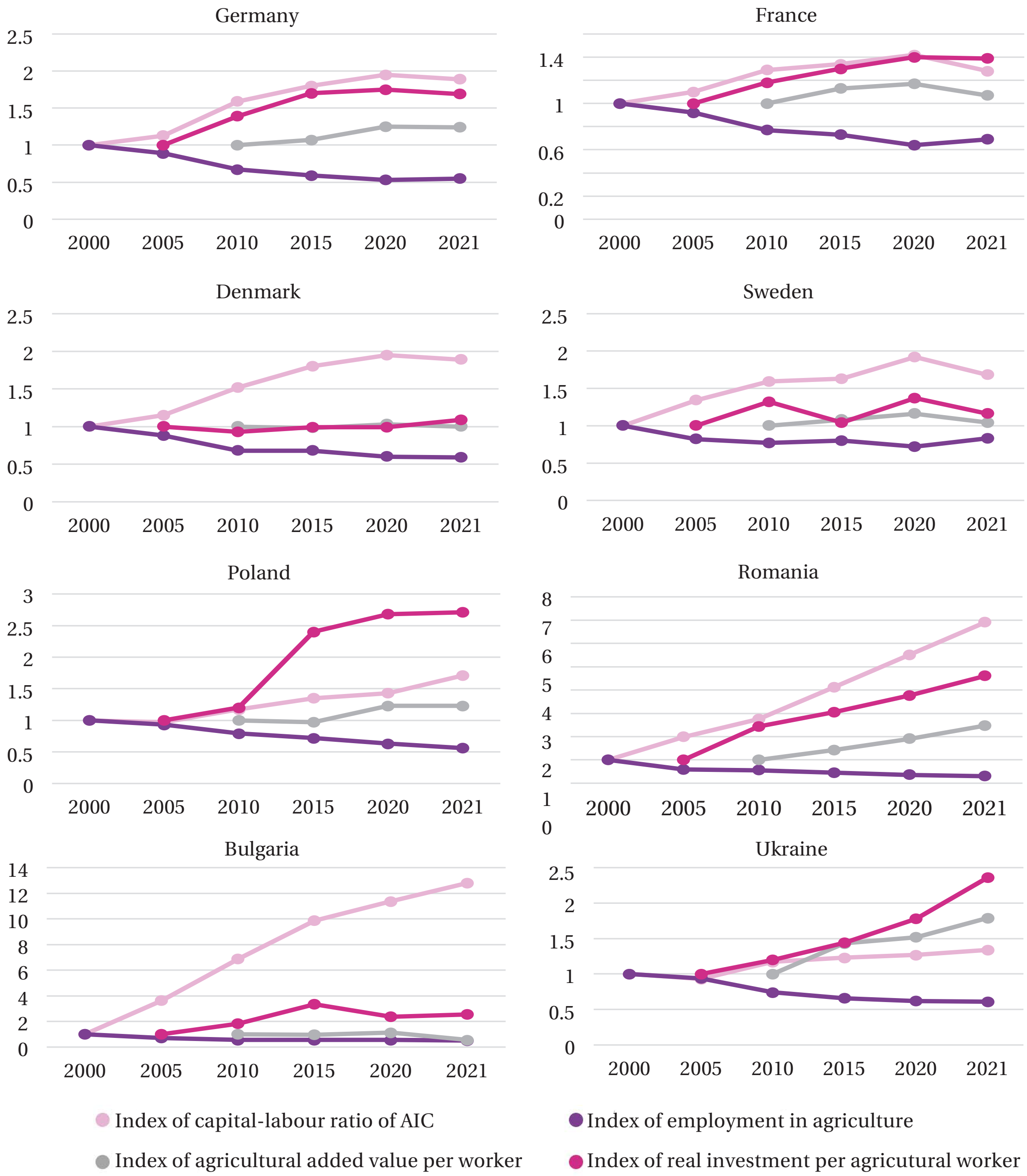

Figure 1. Dynamics of the economic efficiency of the agricultural sector in European countries, compared to the indicators of the year 2000

Source: based on FAOSTAT (2023)

The dynamics of these indicators in European countries with a high level of technological development – Germany, France, Denmark, Sweden – are similar in nature and rate of growth or decline. Thus, capital-labour ratios in agriculture in Germany, France, Denmark and Sweden have increased 1.5-2 times over 20 years, employment in the agricultural sector has decreased by 30-50%, while added value per employee has increased from 10 to 20%. The rate of investment in technical re-equipment of the agricultural sector in Germany and France has increased 1.7-1.8 times over 15 years, while in Denmark and Sweden it has remained consistently high, ensuring their food security and the gradual release of workers from labour-intensive processes. EU countries with the lowest capitalisation of the agricultural sector have a relatively high rate of growth in real investment in the fixed capital of agricultural enterprises: Poland – 2.7; Romania – 4.6; Bulgaria – 2.6. At the same time, the technical equipment of labour in agriculture increased 12.8 times in Bulgaria, 1.7 times in Poland, and 6.9 times in Romania, while the number of employees decreased by 44%, 49%, and 70%, respectively. Characteristically, the growth rate of added value in agriculture per employee does not exceed the growth rate of investment and capital equipment. In Ukraine, however, the dynamics are different: the capital equipment of labour with fixed means of production increased 1.3 times, while added value increased 1.8 times. The data confirm that the increase in added value is not due to technical and technological re-equipment of production, but to the intensive use of land resources, i.e. their depletion. High market demand for grain and oilseeds is prompting Ukrainian farmers to exhaustively use arable land. In particular, there has been a sharp increase in the area under corn, sunflower and rapeseed cultivation. Sunflower cultivation poses a particular threat, as it accounts for more than 30% of the crop structure in some farms.

At the same time, Ukraine, as a supplier of agricultural products to the world market, annually exports significant amounts of nutrients that plants have consumed from the soil to form crops, especially micronutrients, which are not fully compensated for by fertilisers. According to S. Balyuk *et al.* (2019), the grain exported in the 2016-2017 marketing year contained: 811 thousand tonnes of nitrogen, 302 thousand tonnes of phosphorus and 211 thousand tonnes of potassium. To compensate for these losses, it was necessary to apply: 2.4 million tonnes of ammonium nitrate, 0.58 million tonnes of ammophos and 0.53 million tonnes of potash salts. Thus, large agricultural holdings received a significant part of their profits from the use of soil resources and violate natural laws, in particular the law of mandatory compensation (in full) for nutrients removed from the soil. This led to intensive dehumanisation of soils, since 95-97% of nitrogen and about 50% of phosphorus were contained in the organic part of the soil, and their absorption by plants required increased mineralisation of humus. And if the law on the mandatory return of nutrients removed with the harvest was not constantly observed, the soil will become completely depleted in the near future, and even the most fertile chernozems will cease to provide at least some harvest, especially against the backdrop of deteriorating climatic conditions.

Land has been, is, and will remain the main means of agricultural production, and fertility is its main value, which should be preserved for future generations. Ukrainian soils and their preservation require a comprehensive approach and increased attention from the state, farmers, and scientists. According to the FAO, approximately 20% of Ukraine's agricultural land has undergone significant degradation, and the rest is under serious threat. Ukrainian soils have lost about 30% of their humus, and the ploughing rate remains one of the highest in the world at 53.9% (for comparison: in Poland 36.5%, in Germany 34.1%, in the USA 17.5%, in China 12%). The governments of advanced countries strictly protect state interests and consider land to be a valuable resource. In France, in particular, maximum control over its effective use is exercised, exclusively by persons who permanently reside in the relevant area and have the appropriate level of qualification. After testing their level of knowledge and justified areas of use, they receive a licence, and the concepts of ownership and use rights are separated. The procedure for using agricultural land resources in Ukraine currently differs significantly from the above, therefore it needs to be reviewed and a protectionist state policy developed. Land, in particular soil fertility, should be considered as a specific investment resource that provides added value to agricultural products on a par with fixed assets and labour resources. Fertility must be restored and increased, and the value of land must grow accordingly.

Instead, state authorities proudly report on their leadership in global markets for the sale of agricultural raw materials. Despite all these "achievements," even in the successful year of 2021, Ukraine received only USD 7.9 thousand in added value from agribusiness per employee. per employee, while in Bulgaria this figure was USD 18.8 thousand, in Hungary – USD 30.6 thousand, in Germany – USD 58.1 thousand, in France – USD 68.0 thousand, and in Sweden – USD 80.8 thousand. The data presented clearly shows that increasing exports of agricultural raw materials is the wrong path for the development of the agricultural sector. In pursuit of high yields, Ukrainian agricultural producers use a wide range of synthetic plant protection products, which leads to the contamination of soil, water bodies and groundwater. Intensive agricultural production technologies deplete the soil, harm the environment and the health of the Ukrainian population and call into question the food security of future generations of Ukrainians (FAOSTAT, 2023).

In the current conditions of global economic development, raw materials and food supplies are strategic market resources on which national security and sustainable development depend. The core position, shared with the authors led by N. Basyurkina *et al.* (2023) that Ukraine should adopt the experience of advanced countries, whose agricultural policy priorities are: comprehensive support for agribusiness development; ensuring national food security; encouraging exports of processed agricultural products while restricting imports; stimulating the development of own processing industry and imports of agricultural raw materials for its needs. B. Iegorov *et al.* (2024) noted that in Ukraine, as in most countries of the world, grain and its processed products (bread products) form the basis of the state's food security, as they were the main group of food products and animal feed. High calorie content and long shelf life determined the role of grain in the formation of food reserves – it was a strategic product. Bread products satisfied about 40% of the daily food requirement and up to 50% of the protein and carbohydrate requirement. Ukraine's grain policy has undergone significant structural changes, as a result of which the dominance of state interests has been superseded by the priority of exporting agri-food raw materials (Nikishyna, 2012). Such distortions have led to the formation of a raw material model of Ukrainian agri-food exports, the dominance of single-crop production oriented towards the demand of foreign markets, and a decrease in grain processing volumes at Ukrainian enterprises. Such transformational changes contradict the national interests of Ukraine, as they lead to the loss of the reproductive function of the food market while financing the development of the processing industry in countries that export Ukrainian agricultural raw materials. The higher export potential of feed grain and the relatively low cost of its cultivation compared to food grain have led to the predominance of feed in the structure of gross grain harvests. At the same time, Ukraine compensates for the shortage of high-quality durum wheat flour for bread and pasta production by importing the relevant grain or finished products, which leads to job and financial losses due to the reduction of production cycles in the Ukrainian agri-food market.

Taking into account the best practices of the functioning and development of agri-food complexes in advanced countries, it was advisable to focus Ukraine's strategic agricultural policy on stimulating the production of food products with higher added value and increasing the volume of exports of deeply processed products, reducing dependence on imports of grain, products of plant and animal origin, fresh vegetables and seed material. The key task of Ukraine's agri-food sector was to transition from a raw material-based to an investment and innovation-based type of development. At the modern stage of scientific and technological progress in the agri-food sector, the very nature of technologies and production methods was changing. They were becoming more science-intensive, and their implementation requires the use of the latest technology and appropriate organisational support. The transition to advanced robotic information technologies can be called the second "green revolution", as they were changing the established paradigm of agricultural production and taking it to a qualitatively new level.

The European Green Deal (European Union, 2019) in agriculture defined the biologisation of farming as the main tool for improving soil quality and fertility, the key elements of which are: scientifically based soil-protecting crop rotations, modern biotechnological solutions, precision farming technologies, and the balanced use of mineral fertilisers and chemical crop protection products. The transition to the latest technologies in agricultural production, which will ensure the sustainable development and food security of the country, requires the modernisation of the technical and technological base of agribusiness, the development and implementation of innovative, complex, robotic and automated technical means that will ensure high precision and quality of technological operations, their timeliness, energy and resource efficiency. It should be noted that, from the perspective of current research, innovative complex agricultural machinery includes the latest ground-based mobile energy, aviation and transport-technological means, combine harvesters, aggregates, multi-operation technological machines, technological lines, equipment, etc., including computerised and automated systems for controlling their operation and robotic systems for performing technological operations based on new methods of their working bodies' interaction with the soil environment, technological materials, agricultural crops, weeds, microbiota, animals, poultry and agricultural products, ensuring a reduction in specific energy costs, improving the quality of technological operations and minimising the negative impact on the environment.

Due to shortcomings in the organisation of production processes, crop yields depend on natural conditions by almost 80%. At present, the use of precision farming systems allows the impact of climate change on crop production efficiency to be offset and reduced to 20%, while the remaining 80% is determined by the level of technology and management in the agricultural business. By focusing on scientific and technological progress in their development, equipment and technologies have become the most important factors in the efficiency of agricultural production. They determine the level of land productivity, the efficiency and comfort of labour, the cost and quality of products, and shape the social and economic factors of the development of the agricultural sector of Ukraine's economy (Hrytsyshyn, 2024).

The results of current study are consistent with international research emphasising the role of innovation and capital deepening in improving agricultural productivity. According to J.-F. Hulot & N. Hiller (2020), investments in agricultural research and innovation across EU countries generated multi-layered benefits that extended beyond immediate production growth. These included higher resource-use efficiency, environmental sustainability, and long-term resilience of the agricultural system. Their findings demonstrated that every euro invested in research and innovation in the EU agricultural sector can yield up to five times its value in socio-economic returns. In this context, Ukraine's limited investment capacity – USD 963 per agricultural employee in 2021 – highlighted the importance of public policy instruments to stimulate innovation and attract private capital into agribusiness. Y. Sheng *et al.* (2022) also underscore that productivity growth in agriculture across 17 OECD countries was driven largely by capital deepening and induced innovation – the process by which technological change responds to relative factor scarcities and price shifts. Their evidence showed that countries maintaining consistent investment in fixed assets and R&D experienced faster convergence in total factor productivity (TFP). The Ukrainian case, characterised by low capital intensity and technological lag, fits the opposite pattern, suggesting that inadequate reinvestment slows TFP growth and widens productivity gaps with more developed economies. Overall, these insights confirmed that sustainable agricultural modernisation depended not only on capital accumulation, but also on innovation-driven productivity gains and institutional support mechanisms ensuring the effective use of investment resources.

The results of this study aligned with broader international evidence demonstrating that technological modernisation and capital deepening are decisive factors in agricultural productivity growth. According to M. Petrick & M. Kloos (2012), disparities in agricultural capital productivity across EU member states were primarily determined by differences in access to investment resources and innovation intensity. This corresponded with Ukraine's relatively low capital intensity, where limited access to affordable financing constrains the renewal of fixed assets and the introduction of modern equipment. Similarly, T. Kijek *et al.* (2016) emphasised that knowledge capital – human skills, training, and technological awareness – played a critical role in shaping total factor productivity in European agriculture. Ukraine's lag in labour productivity and capital provision suggests an urgent need to invest not only in physical assets but also in education, extension services, and innovation transfer systems. Global evidence from the World Bank's Harvesting Prosperity report (Fuglie *et al.*, 2020) further confirms that sustained productivity growth in agriculture depends on large-scale technological diffusion supported by research, infrastructure, and market integration. Countries that successfully modernised their agro-industrial systems – such as Denmark, the Netherlands, and France – did so by combining targeted subsidies, credit access, and innovation policy incentives. Finally, D. Shen *et al.* (2023) illustrated, using China's experience, how capital deepening can mitigate the effects of a declining rural workforce and enhance labour productivity, reinforcing the broader relevance of technological investment in achieving sustainable agricultural development. Together, these findings underscored that Ukraine's challenge mirrors global trends: to transform agriculture from labour-intensive to knowledge- and capital-intensive production through innovation, financial reform, and state support mechanisms that ensure inclusive, long-term growth.

Therefore, the state should not stand aside from these threats and should stimulate the innovative development of agricultural technologies in Ukraine, the technical re-equipment of agribusiness with innovative Ukrainian ally produced equipment, and ensure the preservation of soil fertility and agroecosystems at the legislative level. The further development of the agricultural sector and maintaining the competitiveness of its products requires the formation of an effective material and technical base (MTB) for agricultural enterprises based on modern innovative transformations. The importance of fixed assets in the development of the agricultural sector in the context of the adoption of new high-performance technologies was constantly growing. The optimal quantity and rational structure of fixed assets, as well as their effective use, ensured not only an increase in production volumes, but also an increase in its economic and social efficiency.

Conclusions

The main factor determining the quantity and quality of agricultural products and the efficiency of Ukraine's agribusiness sector was the level of its material and technical base and its innovative development. Ukraine's agricultural sector demonstrated one of the lowest levels of capitalisation in Europe: the capital intensity of labour amounted to only USD 11.58 thousand per person, which was almost 60 times lower than in Denmark (USD 679.04 thousand) and more than 30 times lower than in Germany (USD 391.01 thousand). The level of capital provision per hectare of agricultural land in Ukraine was USD 0.76 thousand, while in the Netherlands this figure reached USD 40.08 thousand, and in Sweden – USD 18.47 thousand. Labour productivity in Ukrainian agriculture remained critically low – USD 18.71 thousand per employee compared with USD 100.51 thousand in Germany and USD 166.69 thousand in Denmark. Gross agricultural output per hectare in Ukraine equaled USD 1.23 thousand, which was 3.5 times lower than in Italy (USD 4.27 thousand) and almost 8 times lower than in the Netherlands (USD 10.32 thousand). Such disparities clearly indicated the technological backwardness of the domestic agricultural sector and the urgent need for its modernisation. The volume of real investments in fixed capital in Ukraine's agriculture in 2021 amounted to USD 2.64 billion, or only USD 963 per employee, while the same indicator in Sweden exceeded USD 20 thousand, in Denmark – USD 27 thousand, and in Switzerland – USD 31.7 thousand. Investments per hectare of agricultural land were the lowest among the analysed countries – USD 519 per hectare in Ukraine versus USD 1,688 in Denmark and USD 8,620 in the Netherlands. The added value per agricultural worker in Ukraine reached only USD 7.92 thousand, which was 7 to 10 times lower than in most EU countries.

The expanded reproduction, renewal, and modernisation of the technical and technological support of agricultural production in Ukraine required the attention of the state to create institutional and economic conditions for increasing the investment potential of agribusiness, increasing its fixed capital, through the development and implementation of state target programmes, simplifying access to preferential lending, applying leasing mechanisms. Without active state participation and strategic investment, the gap between Ukraine and technologically advanced European countries will continue to widen, threatening national food security and the competitiveness of domestic agricultural products. Prospects for further research may include a more detailed assessment of the effectiveness of different investment mechanisms – such as preferential lending, public-private partnerships, and leasing – in stimulating technological renewal in Ukraine's agricultural sector.

Acknowledgements

None.

Funding

None.

Conflict of Interest

None.

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Матеріально-технічна база агробізнесу в країнах ЄС та Україні

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▸ **Анотація.** Метою цієї статті було оцінити забезпеченість сільського господарства України основними засобами виробництва, ефективність їх використання та оновлення у порівнянні з країнами Європейського Союзу, а також визначити вплив технологічного рівня аграрного сектору на його ефективність. Дослідження було проведено на основі офіційних статистичних даних Організації Об'єднаних Націй. Було здійснено порівняльну оцінку сучасного рівня забезпеченості основними засобами аграрного сектору європейських країн і України. Виявлено, що підвищення технологічного рівня сільськогосподарського виробництва забезпечує зростання доданої вартості в аграрному секторі України, підвищення продуктивності праці, ефективності діяльності та скорочення чисельності працівників. Проведено аналітичні дослідження динаміки та ефективності інвестування основного капіталу в аграрному секторі європейських країн із різним рівнем матеріально-технічного забезпечення. Встановлено, що показники забезпеченості та формування основного капіталу українських сільськогосподарських підприємств, продуктивності праці та доданої вартості в аграрному секторі країни є найнижчими серед країн Європи. Це стало наслідком низького рівня інвестиційних можливостей господарств, що призвело до поглиблення техніко-технологічної відсталості галузі та становило загрозу продовольчій безпеці України. Визначено, що одним із головних чинників, які зумовили кількість і якість сільськогосподарської продукції та ефективність агробізнесу України, став рівень матеріально-технічних ресурсів і їх інноваційний розвиток. Розширене відтворення, оновлення та модернізація техніко-технологічного забезпечення сільськогосподарського виробництва України потребують активної ролі держави у формуванні інституційних та економічних умов

▸ **Ключові слова:** сільське господарство; основні засоби; основний капітал; технічне переоснащення; реальні інвестиції

Received: 23.04.2025. Revised: 28.08.2025. Accepted: 01.10.2025.

EKONOMIKA APK

https://doi.org/10.32317/ekon.apk/5.2025.48

Ekonomika APK, 32(5), 48-62

UDC 338.1:005.336.4:383.2

Trends in the development of Ukrainian agribusiness in the conditions of martial law

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▸ **Abstract.** This study presented a comprehensive bibliometric analysis of the impact of the Russian-Ukrainian war on agribusiness management. Drawing on a dataset of 742 academic publications from the Scopus database (2014-2024), the study tracked how business-related themes have evolved during the war, shedding light on the broader socio-economic context in which these themes are embedded. The analysis highlighted the interconnected nature of research across disciplines, illustrating how broader studies on geopolitical conflict, trade disruptions, and humanitarian issues serve as a backdrop for more focused inquiries into agribusiness management. This layered approach allowed for a clearer understanding of the war's influence on firms' operational environments, the challenges posed to continuity, and the adaptive responses undertaken by companies within and beyond the conflict zone. The results of the study identified seven key areas of agribusiness management affected by the war: retention of personnel and workforce safety, market diversification, business relocation, the launch of new business lines, ensuring functionality under force majeure conditions, maintaining and protecting sales markets, and strengthening information protection and cybersecurity. By synthesising prior inquiries, this analysis underscored common themes, highlighted key research gaps, and suggested future directions for research and practice. A paradigm for the formation of an agri-startup that will contribute to increasing economic stability and the development of agribusiness has been proposed

▸ **Keywords:** war; startup; management; economics; personnel

▸ Introduction

Ukraine's agricultural sector is not merely a business enterprise but a pivotal factor in the country's economic stability. Despite the ongoing war, blockades and global crises, agribusiness continues to supply food to the world

▸ **Suggested Citation**: Biliavska, Yu., Umantsiv, Yu., Osetskyi, V., & Mamchur, V. (2025). Trends in the development of Ukrainian agribusiness in the conditions of martial law. *Ekonomika APK*, 32(5), 48-62. doi: 10.32317/ekon.apk/5.2025.48.

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whilst supporting the national economy. The study of wars and conflicts represents a timeless topic of academic enquiry, and it is therefore unsurprising that numerous contemporary scientific investigations are devoted to brutal military conflicts occurring worldwide. These include the war in Yemen, as examined by A. Mukashov *et al.* (2022), clashes between Hamas and Israel, as examined by H. Mahmoud & S. Abuzerr (2023), and mass protests against governments in Haiti, Georgia and Kyrgyzstan, analysed by E.G. Rød (2019). Further scholarly attention has been directed towards the civil war in Ethiopia by B.A. Nigatu (2023), as well as protests against the regime in Iran (Amini *et al.*, 2024). A distinctive feature of present-day wars is that they encompass not only armed conflicts but also information wars, trade wars, and confrontations with bacteriological threats (Chen *et al.*, 2023; Ju *et al.*, 2024). In such situations, meaningful conclusions from scientific enquiries tend to be derived from investigating the peculiarities of people's daily lives, shedding light on which aspects of socio-economic structures have changed, where deterioration trends are occurring, and at what stage the country's life cycle stands. After all, all wars end sooner or later, and socio-economic structures will need to be revived and renewed. These socio-economic processes are closely interconnected with business activity, shaping the micro- and macroeconomic indicators of organisational environments. The key challenges faced by agribusinesses in the war context are related to ensuring uninterrupted operations, securing short-term profit and achieving long-term business longevity.

The focal war, lasting over a decade now and culminating in the massive Russian invasion in February 2022, brings to life major challenges for businesses in different industries and across different countries way beyond the East European region. This context provides a fertile ground for the growing stream of rigorous studies investigating, e.g., the impact of war on business and society, the global impact of sanctions imposed on the aggressor, the disruptive global impact of war on global supply chains, and the market impact of the war on European listed banks (Klose, 2024; Tsang *et al.*, 2024). Yet, of course, the primary focus of the emerging management literature on the Ukrainian-Russian war is on Ukrainian business management itself, which has faced many challenges during the study period. The coronavirus pandemic has led to a large-scale reduction in production and operations redesign, and companies have suffered significant material losses. The full-scale Russian invasion of 2022 has harmed business for years to come due to the destruction of critical industrial infrastructure, economic collapse, and labour shortages. An exemplary investigation of this issue was presented by K. Obłój & R. Voronovska (2024), who demonstrated how large Ukrainian companies respond to the war-induced crisis through the mechanisms of threat-rigidity and contingency perspectives (in the initial and later stages, respectively).

Importantly, in the face of negative trends, the socio-economic structures underpinning the key challenges faced by agribusinesses enterprises in Ukraine might undergo both negative and positive changes, and transformation processes might lead to the construction of new innovative structures. Tracking these changes was the primary motivation for the current study. Concentrating on the most vivid ongoing military conflict in Europe, the Ukrainian-Russian war, the present study aimed to analyse the trends in the key challenges faced by agribusinesses management in times of war through bibliometric analysis of academic publications from 2014 to 2024. Based on this purpose, the study solved the following tasks: conducting a bibliometric review of literary sources to identify key clusters and scientific directions regarding the negative impact of war on agribusiness; analysing the impact of war on key areas of agribusiness; justify the paradigm of agribusiness development through the implementation of a startup.

▸ Literature review

The importance of studying the war context is underscored in the case study by W.M. Lim *et al.* (2022), who evaluated the impacts of the Ukraine-Russia war on business and society. Their analysis highlighted the multi-dimensional effects of war, which include societal disruptions both within and outside the conflict zone, such as limited access to necessities, increased unemployment changes in the labour market, and inflation. For businesses, the war poses threats such as cyberattacks, disruptions to digital and sustainable growth, and challenges to business ethics and brand management. These insights emphasise the need for a more comprehensive approach to understanding the impacts of the war, which is precisely the aim of the current bibliometric analysis.

In addition to the described above case-based exploration of the implications of the Ukraine-Russia war on business and society, a set of recent empirical papers highlight the global importance of this context from the perspective of different management disciplines. For example, in finance, A. Soliman & E. Le Saout (2024) revealed the impact of the war on idiosyncratic risk, market portfolio volatility, and the relationship between them within the European economies. The results of the study showed that there was an increase in market portfolio volatility and idiosyncratic risk on the whole continent after the military outbreak. Similarly, E. Keleş (2023) demonstrated the heterogeneity of the adverse reaction of stock markets to the war. In terms of global finance, the war may have created an unexpected ripple effect on blockchain and FinTech stocks (Abakah *et al.*, 2023). The impact of war-caused geopolitical risks on foreign exchange markets through fluctuations in foreign exchange rates was presented in A.T. Hossain *et al.* (2024). This adverse impact of geopolitical risks is more pronounced in countries with high dependence on Russian energy, countries with high levels of economic policy uncertainty, and countries with geographical proximity to Russia and Ukraine. Moreover, evidence from the war in Ukraine suggests that, for diversification purposes, gold and bitcoin are complements, not substitutes, in times of crisis. However, during wartime, the gold/bitcoin ratio tends to decline (Oosterlinck *et al.*, 2023). Similarly, the war has had a significant impact on international business: export and import operations, global food supply, and green innovations (Ahn *et al.*, 2023; Rose *et al.*, 2023; Zhu *et al.*, 2024). As such, there is a vibrant and growing body of conceptual and empirical literature that explores different aspects and impacts of the Russian-Ukrainian war on business management, underscoring its global economic fallout that extends well beyond the immediate regions involved (Russia, Ukraine and Eastern Europe).

To systematically capture and synthesise the existing body of knowledge, a bibliometric analysis emerges as a particularly suitable methodology. N. Donthu *et al.* (2021) argued that bibliometric analysis allows for identification of key themes, trends, and research gaps across large bodies of literature. In this context, bibliometric analysis offers unique insights into how business management scholarship has engaged with the war, revealing patterns of inquiry, emerging areas of interest, and interdisciplinary linkages. By generalising and expanding upon prior inquiries, this approach highlights shared themes and recurring issues, thereby creating a more holistic understanding of how the war has influenced business management. While there have been informative bibliometric reviews of the broader societal impacts of the Russian-Ukrainian war, a noticeable research gap exists regarding business management specifically. Previous bibliometric studies have examined the war's effects on global food systems, as demonstrated by T. Ben Hassen & H. El Bilali (2022), H. Gheibdoust *et al.* (2023), and P.R. Chowdhury *et al.* (2023). Further scholarly attention has been directed towards humanitarian law by E. Orzhynska *et al.* (2024), public health by A.A. Sokan-Adeaga *et al.* (2023), and international trade (Paryan & Al Hashfi, 2023). However, bibliometric studies focused on the specific topic of business management remain notably absent from the existing literature. An exploration of the available bibliometric reviews related to the Russian-Ukrainian war reveals that, to date, there is absence of works that explicitly analyse the business management domain. The current study addressed this gap by focusing specifically on the role of the war in shaping business management discourse, offering an original contribution to the field. In the sections that follow, a systematic bibliometric analysis was presented to summarise the body of distinct literature on business management, focusing on the Russian-Ukrainian war. This analysis builds on prior bibliometric methodologies, as suggested by O. Ellegaard & J.A. Wallin (2015), M. Aria & S. Cuccurullo (2017), to identify emerging common themes, highlight research gaps, and suggest future research directions. The approach allows for tracing of interdisciplinary links between various scientific research fields, further advancing the understanding of how the war has shaped business management thought and practice.

▸ Materials and methods

The methodological basis of the study was represented by general and special scientific approaches and methods. The dialectical approach allowed to formulate the philosophical aspects, factors and conditions of business management in wartime. Based on the critical (evaluative) approach, contradictions, critical aspects and paradoxes during the war were identified that affect not only the economy of a particular country but also the world. The general scientific approach was the basis for the formation of prerequisites, trends, patterns and trends in the sustainable development of enterprises during and after war. The application of systemic and synergistic approaches allowed for forming a holistic view of entrepreneurship in war and international activities, as well as to form a mechanism of development based on self-organisation and emergent behaviour.

This study's methodology was based on a comprehensive bibliometric analysis of academic publications spanning from 2014 to 2024, which are related to the impact of the Russian-Ukrainian war on socio-economic and business management systems' dynamics. This period captures the war from its beginning to the phase of a full-scale invasion in 2022 and up to this date. The decision to utilise bibliometric analysis as the core methodological approach was underpinned by several key considerations and strengths inherent to bibliometric methodologies. Similarly to systematic literature review, like the one by M. Orra (2021), as a methodological framework, bibliometric analysis offers an objective and systematic means of reviewing and analysing scholarly publications. This approach is particularly advantageous for mapping out the evolution of research across different scientific fields and identifying the most influential works and authors (Broadus, 1987). In the context of this study, such an analysis allowed for a detailed examination of the breadth and depth of research concerning the socio-economic impacts of the Russian-Ukrainian war, highlighting how these impacts are perceived and addressed across various disciplines. Another crucial strength of bibliometric analysis lies in its ability to provide a comprehensive overview of the research landscape. This is achieved through the evaluation of publication patterns, citation networks, and keyword frequencies, which together offer insights into prevailing research trends, emerging themes, and potential gaps in the literature (Ellegaard & Wallin, 2015). For a topic as multifaceted and dynamically evolving as the Russian-Ukrainian war, such a holistic view is invaluable for capturing the complex interplay between socio-economic factors and business management challenges. Furthermore, bibliometric analysis facilitates the identification of interdisciplinary research insights. Given the diverse implications of the war on society, economy, and the environment, understanding these impacts requires a cross-disciplinary perspective. By analysing citation networks and co-authorship patterns, this methodology uncovers the collaborative nature of research efforts and the integration of diverse scientific domains, underscoring the imperative for interdisciplinary approaches in addressing the war's consequences (Waltman, 2016).

The methodology's emphasis on quantitative evidence of research impact and collaboration adds another layer of depth to the analysis. Through the use of advanced bibliometric tools and software, such as Scopus for data retrieval and VOSviewer for data visualisation, the study not only identified the most influential publications and authors but also mapped out the geographical and institutional distribution of research activities. This quantitative dimension supports the identification of key research clusters and networks, offering insights into the global response to the socio-economic challenges posed by the war. In executing this bibliometric analysis, the authors relied on the Scopus publications and citations database to curate a dataset of academic studies in the focal area. The following sections provide the findings from this analysis, starting with the bibliometric data on the Russian-Ukrainian war for all scientific fields and then delving into the focal area of business management in wartime.

▸ Results and Discussion

Ukraine is a developed industrial and agricultural country with a diversified agricultural sector. However, the full-scale invasion by the Russian Federation on 24 February 2022 had a profound impact on farmers. Accordingly, it also affected export potential and all established logistics routes for shipping and selling products. The full-scale war has been a real test for Ukrainian farmers, as the invasion has destroyed processes and logistics chains that had been established over many years. A significant part of the cultivated land has been mined, and some of it is inaccessible, while equipment and production warehouses have been destroyed. Since the beginning of Russia's full-scale invasion of Ukraine, agri-food products have become a key export item and source of foreign exchange earnings for Ukraine, significantly surpassing the mining and metallurgical complex, which has traditionally been one of the largest sources of export revenues (Table 1).

Table 1. Structure of foreign exchange earnings by export group in Ukraine in 2021-2024, million USD

Names of groups of goods	2019	2020	2021	2022	2023	2024
Food products and raw materials for their production	22,123	22,161	27,687	23,380	22,001	24,665
Mineral products	4,405	4,963	7,874	4,109	2,262	3,137
Products of the chemical and related industries	2,171	2,308	3,173	1,668	1,329	1,508
Wood and wood products	1,780	1,758	2,491	2,118	1,719	1,660
Industrial products	697	722	946	569	557	577
Ferrous and non-ferrous metals and products made from them	9,994	8,782	15,719	5,881	3,888	4,420
Machinery, equipment, vehicles and appliances	3,426	3,390	3,819	2,281	2,150	2,012
Other	1,495	1,059	1,404	893	772	900

Source: compiled by the authors based on National Bank of Ukraine (n.d.)

Thus, at the end of 2021, the share of the agricultural sector in the structure of foreign exchange earnings was almost 44%, and in 2022 it grew to 57% and continues to grow, while the total volume of exports has decreased. The increase in agricultural exports was partly due to the sale of previously accumulated grain stocks. The increase in the share of the agricultural sector in total exports means that the economy is becoming more dependent on its condition and, therefore, on the risks that affect the stability of agricultural production and exports. Among the key threats, experts and market participants cited mined territories, complicated logistics, price volatility, and trade restrictions, which farmers have been facing for several years.

Most of Ukraine's territory is occupied by agricultural land at the beginning of 2020, it accounted for 68.5% of the country's total area. In addition to direct occupation (more than 18% of Ukraine's territory according to DeepState (n.d.) as of mid-March 2025), due to military actions, a significant part of Ukraine's territory up to 30%, especially in the south and east of Ukraine is mined, which is a significant challenge for agricultural production and logistics. The mined territory is not only an internal problem for Ukraine. It leads to increased risks for global food security. Before the full-scale invasion, Ukraine produced enough agri-food products to feed 400 million people worldwide per year. Prices for Ukrainian agricultural products, both on the domestic market and for export, depend on many factors, including the situation on global markets (supply and demand), harvest forecasts, weather conditions, military actions, currency fluctuations and the geopolitical situation, so they fluctuate quite significantly. Russia's attack on Ukraine in 2022 was a shocking event that drove up prices for agricultural products on the global market, although the situation on the markets eventually stabilised. For example, global prices for sunflower oil (Ukraine is the world leader in exports of this product) rose in 2024 amid limited supply, while wheat prices fell to a four-year low as a result of increased global production.

The war is putting extra pressure on Ukrainian businesses, which is affecting profitability – from direct shelling of farmland, businesses, and grain elevators to shortages of resources and human capital and higher logistics costs. Thus, in 2022, the production of major types of grain and oilseeds became unprofitable, but during 2023, the situation improved thanks to the resumption of exports from Ukrainian seaports, which reduced logistics costs and contributed to an increase in purchase prices on the domestic market. January 2025 began with rising prices for major types of grain crops both in Ukraine and abroad. On the one hand, Ukrainian suppliers shipped goods gradually, trying to sell their products on the most favourable terms. On the other hand, on 1 December 2024, the Cabinet of Ministers of Ukraine obliged the Ministry of Agrarian Policy to set minimum export prices for a specific list of agricultural products. In this way, the government plans to combat shadow exports and influence prices on the domestic market. Experts note that winter is traditionally a "high" season when prices for grain, for example, reach their highest levels. In its October report, the World Bank forecasts a 4% decline in global agricultural prices this year due to improved growing conditions and increased production in key regions. According to forecasts by the Institute of Agricultural Economics of Ukraine, the volume of agri-food production in Ukraine will grow in 2025, mainly due to grain and leguminous crops.

At the beginning of the full-scale invasion, Russia blocked the operation of Ukrainian ports, which led to a halt in exports through traditional channels. Restricted access to Black Sea ports forced producers to find alternative routes and pay extra for military risks. In particular, Ukrainian companies redirected exports through European ports, to which grain was delivered by rail or road. Ukraine is actively working to expand its export capabilities through ports on the Danube, in particular Reni, Izmail and Ust-Dunaysk. However, their throughput capacity is significantly lower than that of large Black Sea ports, which limits export potential. Despite Russia's constant attacks on Ukrainian ports, the export corridor is functioning and ensuring the export of the majority of grain products. The high level of military threats remains a key risk to the stability of logistics.

After the start of the full-scale war, the EU completely opened its markets to Ukrainian agricultural products and introduced Solidarity Lanes – alternative logistics routes for Ukrainian suppliers through Eastern European countries bordering Ukraine. On the one hand, this has led to a significant increase in the presence of Ukrainian products on the local markets of some countries (Poland, Hungary, Slovakia). Since 2022, European countries have become and remain a key market for Ukrainian products. This sparked protests among local farmers, who claimed that cheaper Ukrainian products were "crowding out" domestic producers. Poland, Hungary, Romania and other countries temporarily banned imports of Ukrainian grain and other goods, disrupting export chains that had been set up under the difficult conditions of wartime. The issue of Ukrainian product supply to the EU remains in focus in the formation of the Common Agricultural Policy, both before and after Ukraine's full accession to the EU. On the one hand, Ukraine must implement legislative changes, including standards in the agro-industrial complex, aimed at harmonisation with EU norms, and develop capable state institutions. On the other hand, a communication campaign needs to be conducted within the EU to explain the benefits and synergistic effects of a shared future. Continued state and international support for the agricultural sector is important for the further recovery of the industry in terms of both yield and production volumes and sales abroad, although some factors, such as weather conditions, are difficult to influence. Both the above-mentioned state funding for demining and the further development of war risk insurance mechanisms for exporters are important here. The priority remains to establish a common vision with European countries so that Ukraine is perceived not as a competitor but as a reliable partner.

Before proceeding to the analysis of the narrow body of literature on the impact of Russian-Ukrainian war on agribusinesses management, it is crucial to first map a broader literature looking at all aspects of the war. The rationale for this choice is that agribusinesses management domain does not exist in isolation; rather, this area is embedded into the broader social context (Lim *et al.*, 2022). As such, the analysis begins with the bibliometric study of Russian-Ukrainian war across all disciplines. The authors of this study did not impose any restrictions on publication language or country of origin, ensuring a comprehensive and inclusive dataset reflecting the global scope of the war's impacts. The subsequent analysis, aided by VOSviewer software, enabled the visualisation of complex relationships and trends within the literature, illuminating both well-established and nascent research areas. However, for the purposes of the current study, publications from 2014 are relevant because it was then that Russia's first interference in Ukraine's independence took place. The recorded increase in the number of publications coincided with military actions by Russia and the commission of war crimes after February 24, 2022. Given the rapid increase in the number of publications, the authors decided to analyse network connections by keyword, country, and also to investigate the affiliation by authors. As a result of the bibliometric analysis of scientific papers using the functionality of the VOSviewer software, a bibliometric map of publication relationships for the period from 2014 to 2024 was obtained (Fig. 1). The unit of analysis was "Ukraine war", which in turn allowed for filtering the data by such parameters as co-occurrence and all keywords and to obtain a map consisting of 17,687 keywords and 887 meeting the threshold.

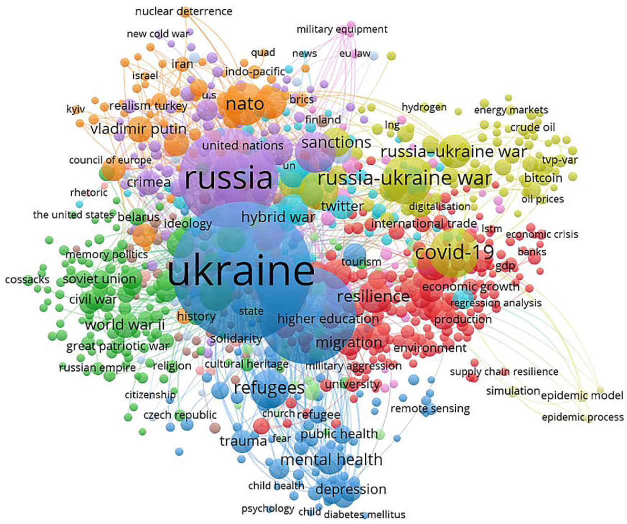

Figure 1. Network visualisation of the term "Ukraine war" in 2014-2024
Source: compiled by the authors

Using the capabilities of the VOSviewer software, the keywords were divided into 8 main clusters using the method of relationship density. These clusters emerged from grouping scientific papers presented in the Scopus scientometric database. The automatic creation and export of a document to CSV format allowed for summarising data such as author, title, year of publication, affiliation, and keywords. In terms of keywords (Table 2), most often, the authors refer to "Ukraine" (1,568 occurrences), "war" (775 occurrences), "Russia" (799 occurrences), "NATO" (147 occurrences), "conflict" (112 occurrences), "war in Ukraine" (203 occurrences). Such keywords are common and are presented in the works of different clusters. The study of the network visualisation of the term "Ukraine war" found that scientific papers cover research on the war in Ukraine in various areas. The authors examine the impact of the war on the mental and psychological health of the population, the preservation of cultural values and resources, historical aspects, education and art, and human resources management. This leads to the conclusion that the war is rapidly making its own adjustments to the country's society, its economic aspects, and international activities.

As a result of network data visualisation, clusters were formed that summarise scientific papers in a particular

Table 2. Formation of scientific clusters on the negative impact of war on agribusiness

Clusters	Keywords of the cluster	Cluster name
Cluster 1 (184 keywords)	resilience, sustainable development, analysis, bibliometric analysis, crisis, economic crisis, economic development, financial stability, financial market, import, export, development, optimisation, blockchain, crisis management, European integration	Resilience
Cluster 2 (131 keywords)	world war, army, civil war, collaboration, constitution, history, Cossacks, great patriotic war, autocephaly, historical memory	World war
Cluster 3 (99 keywords)	Ukraine, war, refugees, terrorism, mental health, child health, psychology, public health, risk factors	War in Ukraine
Cluster 4 (92 keywords)	Russia-Ukraine war, Covid-19, energy, bitcoin, oil and gas, energy security, TVP-VAR, SARS-CoV-2	Force majeure circumstances
Cluster 5 (79 keywords)	Russia, strategic autonomy, realism, Crimea, Black Sea, civilisation, strategic culture	Russian politics
Cluster 6 (72 keywords)	case study, cyber security, cyberspace, e-commerce, Facebook, Telegram, Twitter, information, mass media, news, Russia-Ukraine conflict, journalism	Cybersecurity and media
Cluster 7 (61 keywords)	NATO, China, Iran, Israel, Kyiv, Kharkiv, Japan, Eurasia, Egypt, Canada, Afghanistan	Geography
Cluster 8 (36 keywords)	EU law, global financial crisis, military equipment, drones, de-globalisation, crises, national security, theory, education system	Globalisation processes

Source: compiled by the authors

area. The Red Cluster 1 in Figure 1 and Table 2 indicates a cluster that contains 184 words, and the research area is related to development, commerce, and other management aspects. The illustrative works are A. Wylegała (2023) on international assistance to Ukrainians to resist the war, A. Pawłowska *et al.* (2023) on the protection and preservation of cultural heritage, A. Popova *et al.* (2023) on the development of technological knowledge during the war in Ukraine. An example of crisis management in a Ukrainian university is considered in I. Bohdanov *et al.* (2023). The Green Cluster 2 has 131 words and is related to geopolitical turmoil. The authors pay special attention to the description of the loss of resources and damage suffered by Ukraine during the war (Kussul *et al.*, 2023; Pawłowska *et al.*, 2023). The Blue Cluster 3, which has 99 words, can be clearly identified by the keyword "Ukraine". It demonstrates the direction that combines political, economic and social issues of Ukraine as a country. T. Kuzio (2023) examines the historical aspects of the Russian invasion of Ukraine. Conservation policies and management in the Ukrainian Emerald Network have maintained reforestation rate despite the war are described in L. Shumilo *et al.* (2023). The impact of airborne anxiety on mental health, somatic symptoms, and well-being is described in S. Stieger *et al.* (2023). A number of papers present the peculiarities of the treatment of opioid use disorders during Russia's invasion of Ukraine (Bromberg *et al.*, 2023; Ivasiy *et al.*, 2023). V. Seleznova *et al.* (2023) draw attention to the mental health crisis and the economic aspects of mental health services. The Yellow Cluster 4 (92 words) draws attention to the description of the impact of force majeure during the war, namely changes in the oil market and the economy. The Purple Cluster 5 (79 words) combines research papers describing the peculiarities of Russia's policy during the war, and the papers in the Orange Cluster 7 (61 words) are related to the geographical features and impact of the war on different countries and cities. The Lilac Cluster 8 (36 words) contains the keywords "child", "pandemic", "medical". N. Tsybuliak *et al.* (2023) draw attention to the issues of education in Ukraine and professional burnout among Ukrainian teachers during the war, V. Pavlenko *et al.* (2023) discuss the impact of war on Ukrainian female students.

The publications from the bibliometric analysis related to the field of "Business, Management and Accounting" were selected for further review (n = 742). The authors' team reviewed the titles, keywords and abstracts of each publication in this group in a search of common patterns. The results of this inductive analysis reveal seven broad groups, or business areas affected by the war (Table 3).

Table 3. Research on the impact of war on key areas of agribusiness

Study areas: Agribusiness aspects during the war	Trends within areas: Agribusiness during wartime	Interconnected fields	Sample/notable studies
Retention of personnel and ensuring the safety of personnel in war conditions	Protection of personnel at the workplace during air raids and shelling. Relocation of jobs and processes to safe regions of the country or abroad. Finding ways to minimise costs and payroll opportunities. Replacing the absence of personnel due to service in the Armed Forces or territorial defence. Trauma and psychological distress.	Arts and humanities, social sciences, psychology	V. Halushka *et al.* (2022) V. Pavlenko *et al.* (2023) V. Seleznova *et al.* (2023)
Search for new markets/customers	Repurposing activities and flexibility to produce goods and services that are relevant in a time of war. Participation in volunteering and assistance to the army. Cooperation with international organisations.	Social sciences, economics and finance	M. Pellicelli (2023) J.N. Sheth & C. Uslay (2023)

Table 3, Continued

Study areas: Agribusiness aspects during the war	Trends within areas: Agribusiness during wartime	Interconnected fields	Sample/notable studies
Relocation of agribusiness to another region of Ukraine or abroad	Selection of a location for the company's facilities. Transportation of equipment and setting up operations in the new region. Search for employees and adaptation of relocated employees. Establishing logistics processes, providing raw materials and finding a market. Reengineering of business processes.	Social sciences, economics and finance	C. Balbontin & D.A. Hensher (2019) V. Lazarenko (2020) R. Wehrle *et al.* (2023) V. Lavreniuk *et al.* (2023)
Opening new business lines	Reorientation of business to goods in times of war. Development of startups focused on small businesses. Formation of ecosystems in industry and trade.	Economics and finance	S. Steinbach (2023) K. Obłój & R. Voronovska (2024) Y. Biliavska *et al.* (2025)
Ensuring the functioning of the business in force majeure circumstances	Setting up operations taking into account air raids, power outages, and total resource savings.	Economics and finance	G. Liobikienė *et al.* (2023) M. Izzeldin *et al.* (2023)
Maintaining/protecting current sales markets	Maximum fulfilment of the terms of the concluded agreements. Cooperation with international organisations that can protect business in times of war. Search for investments and investors. Developing effective work plans and short-term strategies.	Economics and finance	I. Aviv & U. Ferri (2023) S. Devadoss & W. Ridley (2024) A. Kostruba (2025)
Information protection and cybersecurity	Compliance with fraud protection rules. Scan, classify, and organise monitoring of confidential information. Develop digital literacy skills. Monitor VPN and DNS connections and block malicious connections.	Social sciences, information technologies, cybersecurity	T. Serafin (2022) U. Song *et al.* (2024) Y. Biliavska *et al.* (2025)

Source: compiled by the authors

The presented areas and research papers identify the specifics of the war's impact on agribusiness and the changes that are taking place in it. These seven areas represent the key dimensions of agribusiness activity that have been reshaped by the war. Each area highlights the unique challenges posed by conflict and illustrates how agribusiness are responding to maintain operational continuity, adapt to new demands, and secure future growth opportunities.

1. Retention of personnel and ensuring safety. The war has posed significant challenges to the retention and safety of personnel, especially in the face of air raids, workplace shelling, and the mobilisation of workers into the Ukrainian Armed Forces. Companies have had to relocate jobs to safer regions and explore cost-minimising strategies, including payroll adjustments. Measures for personnel well-being and psychological support have also gained attention. Notable studies in this area include V. Halushka *et al.* (2022), which addresses training and rotation of military personnel, and V. Pavlenko *et al.* (2023) and V. Seleznova *et al.* (2023), which discuss the psychological distress and mortality risks faced by Ukrainian medical workers.

2. Search for new markets and customers. The disruption of traditional markets has driven companies to repurpose operations and engage in the production of wartime-relevant goods and services. Agribusinesses have also engaged in voluntary support for the armed forces and sought partnerships with international organisations. Flexibility and agility have become essential for survival. M. Pellicelli (2023) addresses the digital transformation of supply chains. J. Sheth & C. Uslay (2023) discuss the B2B market shifts driven by conflict; this study stresses the need important to find new markets and consumers. Ukraine has an export-oriented orientation in foreign markets. This means that the country exports mainly clean raw materials, such as grain, metals, and minerals. Therefore, the development of value-added sectors of the economy is one of Ukraine's priorities in the coming years.

3. Relocation of agribusiness operations. With the destruction of critical infrastructure, many businesses have had to relocate to safer regions within Ukraine or move operations abroad. This involves transporting equipment, establishing new logistics systems, and reengineering business processes. C. Balbontin & A. Hensher (2019) analyse firm-specific and location-specific relocation drivers, while R. Wehrle *et al.* (2023) focus on infrastructure availability's influence on relocation decisions. V. Lavreniuk *et al.* (2023) highlight how host region support plays a crucial role in successful business relocation.

4. Opening new business lines. The war has prompted the launch of new businesses, often cantered around wartime needs, such as clothing for soldiers, essential medical supplies, and drone production. Startups have seen a surge, with military-related small businesses gaining prominence. Studies like S. Steinbach (2023) highlight the redistribution of world trade due to the conflict, while K. Obłój & R. Voronovska (2024) explore how Ukrainian companies have pivoted to seize new business opportunities during the crisis.

5. Ensuring business functionality under force majeure conditions. Operating during force majeure requires companies to develop systems that can withstand air raids, power outages, and resource scarcity. Agribusinesses have been forced to reconfigure operational plans to maintain continuity. Studies by G. Liobikienė *et al.* (2023)

and M. Izzeldin *et al.* (2023) discuss strategies for ensuring business continuity amid war-related disruptions.

6. Maintaining and protecting current sales markets. Maintaining existing sales markets has become a key strategic goal for Ukrainian agribusiness. This involves honouring contract obligations, fostering cooperation with international organisations, and securing investments to sustain production. Researchers such as I. Aviv & U. Ferri (2023) and S. Devadoss & W. Ridley (2024) explore these strategies, T. Czapla *et al.* (2023) discuss measures that allow managing foreign business operations in Ukraine in times of war and cross-cultural and marketing management in international markets. A really important study in this area is arguably A. Kostruba (2025), which examines the challenges and opportunities for managing foreign agribusiness operations in Ukraine amid the ongoing war. Using a combination of legal analysis and case studies, the article highlights the significant disruptions caused by the conflict, such as infrastructure damage, supply chain interruptions, and heightened security risks. The author emphasises the role of government policy, focusing on the introduction of e-residency as a strategic tool to attract foreign entrepreneurs. The e-residency program allows foreigners to establish and manage agribusiness in Ukraine remotely, thus mitigating the physical risks of operating in a conflict zone. The study further explores the legal frameworks governing foreign agribusiness operations, such as the establishment of limited liability companies (LLCs) and the regulation of foreign employment in Ukraine. A. Kostruba (2025) argues that while the war presents severe challenges, it also opens up possibilities for innovation and investment, particularly in areas like IT, energy, and construction, which are vital to Ukraine's post-war recovery. By outlining the regulatory environment, the study provides actionable insights for foreign investors and policymakers aiming to support Ukraine's economic stability and growth during the conflict.

7. Information protection and cybersecurity. The digital environment has become a battleground in itself, necessitating robust measures to protect information and cybersecurity infrastructure. Companies are compelled to secure digital assets, monitor VPN and DNS connections, and counter disinformation. Y. Biliavska *et al.* (2025) emphasise the importance of digital literacy in mitigating cybersecurity risks, while U. Song *et al.* (2024) explore how cyber resilience strategies are being developed. T. Serafin (2022) highlights the role of Ukraine's state-level initiatives to protect social media and counter disinformation in the early days of the war.

Generalising the results of the findings from Table 3, it can be concluded that agribusiness community in Ukraine have to overcome a number of difficulties and take certain measures, such as: (a) relocation – a significant number of small and medium-sized enterprises were moved to the central and western regions due to military operations; (b) adaptation of products and services to modern needs – companies have retrained for goods and services that are in great demand right now, for example, the production of long-term storage products, sewing clothes for soldiers, and the production of UAV (drones). The war that is taking place in Ukraine due to Russia's full-scale invasion has dealt a devastating blow to Ukrainian business; thus, in this study, the authors focus on the impact of the war across industries and business functions. According to the study of the Kyiv School of Economics (2023), as of December 2022 (8 months of full-scale invasion), the total damage to Ukraine's economy was USD 138 billion, including USD 13 billion of direct losses to public and private enterprises. Of these, the share of losses incurred by large and medium-sized enterprises is USD 9 billion. At the same time, the total indirect losses amounted to USD 33.1 billion, while the amount needed to restore these damaged enterprises is USD 24.9 billion.

The IT sector is the best performer in wartime. None of the Ukrainian projects were closed, and hundreds of them received additional investments and were in great demand in the Ukrainian and international markets. These include Skyworker, Trinetix, and RevMyWork. During the war, there is a rapid development of startups and the translation of innovations into real life projects to support the country's economy (Fybish, 2024). The rapid development of veterans businesses has played a significant role in improving the country's economic condition. Veterans and their family members are starting many small and medium-sized enterprises of various profiles: agricultural, catering and coffee shops, small manufacturing companies producing various products. Analysts predict that veteran businesses will be the driving force behind the full recovery of Ukrainian business. According to a survey of the American Chamber of Commerce in Ukraine (2023), the main problems of doing and developing business in Ukraine are: missile attacks on business assets and critical infrastructure; health and mental state of employees; decline in economic and consumer activity; access to electricity, water and heat supply, mobile communications; attracting and retaining top talent; problems with transportation and logistics. Amidst this context, the findings of the current study have broad implications for understanding business management in the context of war. First, they highlight the necessity for businesses to develop contingency plans that account for geopolitical risks and the potential for sudden market and supply chain disruptions. The resilience shown by the Ukrainian IT sector, for example, underscores the importance of flexibility and the ability to pivot business models rapidly in response to external shocks. Furthermore, the research emphasises the interconnectedness of global markets, showing that conflicts in one region can have ripple effects across the globe, affecting economies and businesses far removed from the conflict zone. This global interconnectedness necessitates a more collaborative and coordinated international response to support affected businesses and economies. As such, the current study complement and expand the prior investigations of the business aspects of the war in Ukraine, like those by W.M. Lim *et al.* (2022), A. Kostruba (2025), providing a broader set of implications based on the summary of a major body of scientific literature.

Paradigms for the development of agribusiness in wartime involve searching for alternative solutions that will help overcome the problems identified in the bibliometric review. One such solution is the introduction of startups. Agriculture has been transformed into a new industry called agribusiness. Agribusiness encompasses not only individuals who cultivate the land, but also people and businesses that supply resources, process products, produce food, transport food, and sell food to customers (Bano, 2024). Despite the conditions of war, food remains a key need for the world's population. Consumers are increasingly interested in the origin of products, so many companies now provide detailed information about their products, including the source of ingredients and production methods used. Finally, competition in agribusiness is growing. With the rise of organic and local foods, as well as sustainable farming methods, many small businesses and startups are entering the market. Startups in agribusiness are a new but widespread trend in the world. For example, agri-startups in Africa are described in the work of B.A. Yeboah *et al.* (2024); the formation of factors and technologies of startups in agribusiness in Southern Thailand is studied by N. Kaewsuwan & S. Kajornkasirat (2023), and the agribusiness strategy of startups in the EU is presented in the work of M. Fiore *et al.* (2022). A bibliometric review using the keywords "Agribusiness and Startup" (Fig. 2) shows that the words entrepreneurship, innovation, stability, and development have the highest share.

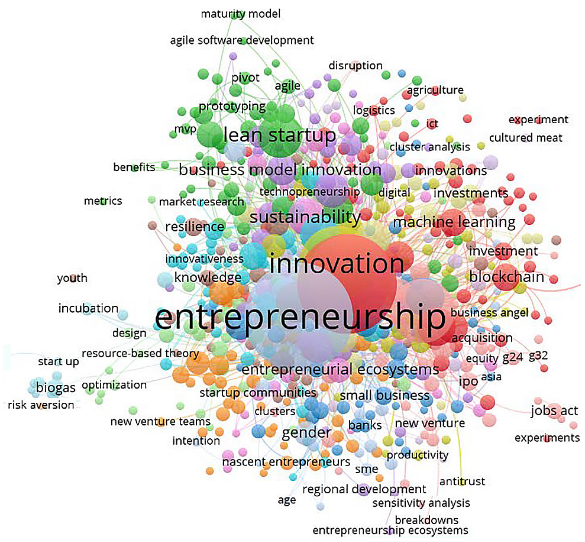

Figure 2. Network visualisation of the term "Agribusiness and Startup" in 2014-2024
Source: compiled by the authors

In the world of innovation and technology, the development of startups is one of the main tasks of the economic policy of the state, individual regions or cities, since from the point of view of economic development, these are long-term investments that, on average, will significantly boost the economic development of the state and add economic stability to the economic system within one or two decades. The state's task is to create an environment that promotes, strengthens and coordinates the process of transforming innovative entrepreneurial ideas and inventions into functioning profitable enterprises. Considering the prospects of startup projects, the authors of this study believe that the creation of agri-startups is a promising trend for Ukraine, which can be implemented through the following steps:

- Step 1. Organising the business as the birth of an idea. This stage involves searching for and forming key ideas, testing and analysing the opportunities for an agri-startup. At this stage, it is important to test consumer hypotheses, engage stakeholders, and register patents and trademarks.
- Step 2. Initial stage. This stage involves finding funding, which in wartime could be a grant or crowdfunding, as this is what will turn the idea into a functioning agribusiness. This is also when experiments, market testing and approval of a minimal but viable product take place.
- Step 3. Early stage of the startup life cycle. If the previous stages have been successfully completed, at this stage a customer base and stable financial income have been established.
- Step 4. Expansion/growth stage. Scaling up the business is an important prospect, but it is important to control resources: capital, raw materials, and personnel.
- Step 5. Stability and development of agribusiness. Provided that the business is run effectively, stability involves searching for new markets and forming strategic prospects for the growth of agribusiness.

Therefore, the development of agribusiness startups in Ukraine during the war is not only a challenge but also an opportunity to form a new innovative economy capable of adapting to modern realities and integrating into global processes. The current state of agribusiness startups in Ukraine, the identification of current risks and the development of solutions to strengthen its development are pressing issues that require careful research and practical solutions.

This article makes several contributions to the field of management. By compiling and analysing data from a wide range of sources on the case of war in Ukraine, it provides a comprehensive overview of the current state of knowledge on the impact of war on business practices, offering insights into areas that are well understood and identifying gaps in the literature. The research also introduces a novel perspective on the role of innovation and adaptability in business survival during times of conflict, adding depth to the discussion on strategic management in volatile environments. Additionally, the study's focus on the Russian-Ukrainian war provides timely and relevant insights into the specific challenges and opportunities presented by this ongoing conflict. Moving beyond business management to a broader scientific body of literature, building a bibliometric map of network visualisation of data by the keyword "Ukraine and war" (Fig. 1) allowed for forming scientific clusters of business interconnection with other scientific areas. This, in turn, demonstrates the interests of scientists and specialists who cover the results of their research in various publications included in scientometric databases, including Scopus. Building on the findings of the current study, particularly the areas of business management, this study identifies several critical avenues for future research on business management amidst the Russian-Ukrainian war. These directions aim to address existing knowledge gaps, provide actionable insights for business practitioners, and contribute to the broader literature on crisis management and business resilience in conflict settings.

1. Deepening understanding of workforce resilience and retention strategies. The retention of personnel and the safeguarding of employee well-being emerged as critical challenges for agribusinesses operating in Ukraine during the war. Future research should explore the development of new human resource strategies aimed at mitigating risks related to worker displacement, psychological distress, and workforce mobilisation into the armed forces. Longitudinal studies on workforce adaptation could provide insights into how agribusinesses sustain employee morale and productivity under prolonged crisis conditions. Investigating how agribusinesses support employee mental health and well-being, especially in industries where trauma exposure is high, could offer valuable lessons for global crisis management frameworks.

2. Exploring agribusiness relocation and supply chain adaptation. Relocation of agribusiness operations, particularly for companies situated in conflict zones, is a multifaceted process that warrants further investigation. Future research could examine the decision-making criteria for site selection, the logistics of relocating equipment and personnel, and the role of host region support in facilitating smooth transitions. Comparative studies across industries could reveal sector-specific challenges and strategies for effective relocation. Additionally, the broader implications of supply chain reengineering during wartime – such as shifts in sourcing, supplier diversification, and nearshoring – merit further exploration, especially given the increasing complexity of global supply chains.

3. Emerging opportunities for agribusiness diversification and new ventures. The opening of new agribusiness lines in response to the war, such as the production of military-related equipment or consumer goods for displaced populations, represents a fertile ground for future research. Studies could investigate the drivers and barriers to innovation under crisis conditions, particularly the role of digital transformation and startup ecosystems. Further research could explore how war-affected agribusinesses leverage entrepreneurial opportunities, tap into emerging consumer needs, and engage with international development organisations to drive growth. Empirical studies of Ukrainian startups could reveal pathways for fostering entrepreneurial ecosystems in other conflict-affected regions.

4. Digitalisation and cybersecurity resilience in wartime agribusiness management. The digitalisation of agribusiness operations and the heightened need for cybersecurity during the war have brought new challenges and opportunities to the forefront. Future research could focus on how agribusinesses develop cybersecurity strategies to counter disinformation campaigns, manage VPN/DNS monitoring, and prevent data breaches. Studies on the role of government-led digitalisation initiatives, such as Ukraine's e-residency program, could offer important insights into how digital infrastructure supports business resilience. Comparative research on digital preparedness and cybersecurity measures in other crisis-affected countries could identify best practices for future application in volatile environments.

5. Policy implications and governmental support for war-affected agribusinesses. The role of public policy in supporting agribusiness continuity and growth during armed conflict is a vital area for future inquiry. Research could explore the effectiveness of policies such as financial subsidies, grants, and legal frameworks that facilitate the relocation of agribusinesses and protect foreign investments. Case studies on how different governments have responded to agribusiness needs during crises could offer valuable policy insights. In particular, the impact of Ukraine's e-residency program on attracting foreign investment and supporting new ventures could serve as a case study for policy diffusion in other war-affected economies.

By addressing these key areas, future research can provide a more nuanced understanding of agribusiness management in war contexts. These efforts will contribute to the development of practical strategies that businesses, policymakers, and humanitarian organisations can adopt to ensure business continuity, resilience, and long-term recovery in conflict zones. Despite the comprehensive scope of this bibliometric analysis, there are several limitations that should be acknowledged. These limitations pertain to data coverage, methodological constraints, and generalisability of the findings. Addressing these limitations in future research can enhance the robustness and applicability of similar studies.

Data source limitation. The primary limitation of this study is its reliance on the Scopus database as the sole source for bibliometric data collection. While Scopus is a well-established and comprehensive database, it does not encompass all relevant academic publications. Articles from other influential databases, such as Web of Science, PubMed, OpenAlex, and Crossref, were not included. Consequently, the exclusion of these sources may have led to a partial representation of the literature on the impact of the Russian-Ukrainian war on agribusiness management. Incorporating additional databases in future analyses could improve the accuracy of research trend mapping and facilitate the identification of broader scientific clusters.

Timeframe of data collection. The study focused on bibliometric data from 2014 to 2024, capturing publications from the onset of Russian interference in Ukraine to the full-scale invasion and its aftermath. While this timeframe allows for a thorough examination of the war's business-related impact, it may not fully capture the rapidly evolving scholarly discourse on this topic. Given the ongoing nature of the conflict and the continuous emergence of new studies, the inclusion of more recent data in future bibliometric reviews will be essential for capturing dynamic changes and ensuring the study remains current.

Language and regional bias. The analysis included academic publications in various languages but may be subject to language and regional bias. Research articles written in less commonly used languages may be underrepresented, which could limit the study's capacity to identify insights from non-English-speaking academic communities. Additionally, a substantial portion of the literature in the Scopus database comes from Western, Ukrainian, and European research institutions, which could skew the thematic focus and perspectives represented in the analysis. Incorporating publications from additional linguistic and regional sources would provide a more diverse and global perspective on the impact of war on agribusiness management.

Methodological constraints. The methodological approach relies on the co-occurrence of keywords, citations, and the use of network analysis tools like VOSviewer. While these methods are standard in bibliometric research, they have limitations in terms of precision and depth. For instance, co-occurrence analysis is limited by the quality and consistency of keywords assigned by authors and indexers, which may lead to inaccuracies in identifying key themes. Additionally, the use of automated clustering techniques to group articles into thematic areas may miss nuanced distinctions between related concepts. Future studies could employ a combination of manual qualitative coding and automated bibliometric techniques to achieve a more refined understanding of thematic interconnections.

By acknowledging these limitations, the authors of this study provide a transparent account of the study's boundaries and offer directions for future research. Addressing these challenges will strengthen the comprehensiveness, validity, and generalisability of future bibliometric reviews on agribusiness management amidst conflict and crisis scenarios.

Conclusions

This study provided a comprehensive bibliometric analysis of the impact of the Russian-Ukrainian war on agribusiness management, offering valuable insights into how the conflict has reshaped management practices, organisational strategies, and operational resilience. By examining 742 publications from the Scopus database, the study identified key trends and thematic areas, including personnel retention and safety, agribusiness relocation, market diversification, digital transformation, and the protection of information assets. The seven identified agribusiness areas underscore the wide-ranging and profound effects of the war on agribusiness operations, from ensuring workforce stability to the development of cybersecurity frameworks. This analysis highlighted the dynamic responses of agribusinesses and contributes to a growing body of knowledge on strategic management in times of geopolitical crisis.

One of the most significant contributions of this study is its identification of the unique role played by Ukrainian firms in navigating extreme challenges posed by the war. Unlike typical crisis management scenarios, agribusinesses in Ukraine face continuous disruptions from armed conflict, requiring them to adopt more agile, innovative, and risk-tolerant approaches. The analysis illustrated how companies have leveraged relocation strategies, market diversification, and technology adoption to ensure continuity and growth despite adverse conditions. The study also drew attention to the global ripple effects of the war on international supply chains, labour markets, and trade relations, suggesting that the implications of the war extend far beyond the immediate conflict zone.

Overall, this bibliometric review provided a valuable resource for scholars, policymakers, and agribusiness leaders seeking to understand how the war has transformed the agribusiness environment. The findings offer a roadmap for future research, emphasising the need for deeper inquiry into adaptive strategies, cross-sectoral collaboration, and the role of government support in sustaining agribusiness continuity during protracted conflicts. By mapping the literature on agribusiness management amidst the war, this study lays the groundwork for future studies that can offer actionable insights to agribusinesses operating in high-risk and crisis-prone environments. Ultimately, it calls for more collaborative research and policy development to build resilient agribusiness ecosystems that can withstand the shocks of modern geopolitical crises. The study identified the main stages of agricultural startups in Ukraine. It noted that the war has significantly complicated the opportunities for commercialising innovations and scaling up businesses.

Acknowledgements

None.

Funding

None.

Conflict of Interest

The authors of this study declare no conflict of interest.

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Тенденції розвитку агробізнесу України в умовах воєнного стану

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▸ **Анотація.** Дослідження мало на меті провести комплексний бібліометричний аналіз впливу російсько-української війни на управління агробізнесом. На основі набору даних із 742 наукових публікацій із бази даних Scopus (2014-2024 рр.) у дослідженні простежено еволюцію тем, пов'язаних із бізнесом, під час війни, що проливає світло на ширший соціально-економічний контекст, в якому ці теми вбудовані. Аналіз підкреслив взаємопов'язаний характер досліджень у різних дисциплінах, ілюструючи, як більш широкі дослідження геополітичних конфліктів, перебоїв у торгівлі та гуманітарних питань слугують фоном для більш цілеспрямованих досліджень у сфері управління агробізнесом. Такий багаторівневий підхід дозволив чіткіше зрозуміти вплив війни на оперативне середовище підприємств, виклики, що стоять перед безперервністю діяльності, та адаптивні заходи, вжиті компаніями в зоні конфлікту та за її межами. Результати дослідження визначили сім ключових сфер управління агробізнесом, на які впливає війна: утримання персоналу та безпека робочої сили, диверсифікація ринку, перенесення бізнесу, запуск нових напрямів бізнесу, забезпечення функціональності в умовах форс-мажорних обставин, підтримка та захист ринків збуту, а також посилення захисту інформації та кібербезпеки. Узагальнюючи попередні наукові напрацювання, цей аналіз підкреслив спільні теми, висвітлив ключові прогалини у знаннях та запропонував майбутні напрями для досліджень і практики. Запропоновано парадигму формування агростартапу, який сприятиме підвищенню стійкості економіки та розвитку агробізнесу

▸ **Ключові слова:** війна; стартап; управління; економіка; персонал

Received: 03.06.2025. Revised: 03.09.2025. Accepted: 01.10.2025.

EKONOMIKA APK

https://doi.org/10.32317/ekon.apk/5.2025.63
Ekonomika APK, 32(5), 63-78

UDC 338.2/338.3/631.1

Scenario analysis of the degree of depreciation of cereals yield and milk yield in the context of Ukraine's economic security

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▶ **Abstract.** The purpose of this study was to model the dynamics of indicators of Ukraine's industrial and food security against the background of strategies for increasing organic land and scenarios of hostilities until 2030. The methodological basis consisted of both time series models that considered exogenous variables and multifactor linear regression models. It was established that a decline in the degree of fixed asset depreciation in agriculture by 0.15 p.p., resulting from a 1 p.p. growth in the share of organic land, wasn't pose a threat to Ukraine's industrial security, but it couldn't offset the destructive consequences of the russian-Ukrainian war. While setting a target of 10% organic area will brought cereal yields (64 c/ha) closer to the optimal state (45-55 c/ha) with a weighted average yield loss of 1.97 c/ha in 2030, corn yields, even with losses (2.60 c/ha), will remain in an unsatisfactory state, reaching 75 c/ha. Although the average annual milk yield will predict to accomplish a satisfactory state in 2028 (5,521.2 kg>5,000 kg) under the baseline forecast, the yield losses (amounting to 119.89 kg) associated with a more than 10% organic livestock will prevent this achievement by 2030. Therefore, accelerated development of organic dairy production couldn't be recommended under any of the scenarios. However, achieving a 3% share of organic cows wasn't jeopardise industrial security (except for the pessimistic war until 2030). Given the critical condition of milk self-sufficiency (<80% starting from 2025), which was the consequence of a steady reduction in the number of cows, organic dairy production exacerbated the problem of food insecurity. The study results can be used by Ukraine's executive authorities in developing substantiated strategies for the transition to organic agriculture that will meet the goals of economic security

▶ **Keywords:** industrial security indicators; war scenarios; strategy; organic production development; milk self-sufficiency; food insecurity

▶ Introduction

Ukraine's agriculture was a critically vital sector of its economy, squarely or indirectly influencing the state of economic security indicators. The russian full-scale invasion dealt a substantial blow to Ukraine's agricultural sector, thus jeopardising both its industrial and food security. Under these conditions, forecasting the dynamics of individual indicators of economic security components proved crucial for economic planning and ensuring agricultural development during the 2026-2030 period. The agricultural sector of Ukraine and its relationship with the industrial and food components of economic security have become a subject of intense research, particularly in the context of full-scale hostilities.

V. Lagodiienko *et al.* (2022), determining modern food security level using a developed thorough system of indicators consisting of components (affordability, availability, quality and safety, sustainability, and adaptation), identified its bottlenecks in the context of the ongoing war with russia and global crises, such as the COVID-19 pandemic. A. Podsokha *et al.* (2023) examined the potential for improving food security, detailing levels of self-sufficiency in various food categories, and concluded that the production of milk and dairy products, fruits, berries, and grapes in Ukraine did not fully meet consumption in 2020-2021. However, their model was built on historical data up to 2021, and, therefore, did not consider the impact of a full-scale invasion and various scenarios of its completion. V. Hobela *et al.* (2022) called for a modernisation of the agro-industrial complex, given that Ukraine's food security was lower than the average world and European

▶ **Suggested Citation**: Hurtovyi, Yu. (2025). Scenario analysis of the degree of depreciation of cereals yield and milk yield in the context of Ukraine's economic security. *Ekonomika APK*, 32(5), 63-78. doi: 10.32317/ekon.apk/5.2025.63.

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indicators in 2022. Although the authors forecast its level until 2027, the effect of full-scale war was not integrated as an independent variable.

Researchers O. Petrenko (2025), focusing on the yield of major crops, determined their losses by comparing alternative yields in the absence of a military shock with actual indicators in 2022-2023 using Autoregressive Integrated Moving Average with Exogenous Variables (ARIMAX). S. Kaushik & N. Bhardwaj (2024) showed that the integration of exogenous variables in the ARIMAX model, i.e., climatic data, allowed for more accurate forecasts, surpassing the results obtained by ARIMA models. The study by A. Kulyk *et al.* (2025) indicated that the use of the seasonal ARIMAX model provided the best forecasting accuracy, contributing to more effective planning of business processes, optimisation of production, and competitiveness of the agricultural industry. Scientists M.A. Omar *et al.* (2024) carried out forecasting of future milk production volumes, using ARIMAX without considering any external factors, compared to the study of previous authors. But, the results of this researchers could not be applied to assess the state of the dairy industry of Ukraine in the context of industrial or food security.

N. Strochenko & O. Kovalova (2025) revealed a critical level of fixed assets depreciation in agricultural enterprises, proposing solutions through innovation and investment activities. However, uncertainty related to the full-scale war called into question the feasibility of implementing high-tech solutions. Therefore, for an objective planning of investment and innovation activities, the need arose to model the degree of fixed assets depreciation depending on the intensity of hostilities under several scenarios. I. Kryukova & M. Ihnatenko (2025) found that the influence of hostilities restrained and limited the potential for the renewal of agricultural machinery, and therefore should be considered, when analysing the degree of fixed assets depreciation. According to the authors, their modernisation should consider the need for economic, environmental, and social sustainability, and organic farming was a component of one of these sustainable development dimensions. R. Lobai (2024) emphasised that the renewal should meet modern market requirements, and therefore focused on the production of crops with high added value and food grown according to the organic model to gain competitive advantages. S. Amons (2021) mentioned that the development of organic agriculture in Ukraine in the future will allow to promote innovative development, that was, had been a catalyst for modernisation and technological renewal of agricultural enterprises. R. Lohosha (2025) emphasised that the development of organic production was necessary not only to increase the competitiveness of Ukraine's agricultural sector, but also was a prerequisite for Ukraine's integration into the European space. The study aimed to forecast the dynamics of key agricultural indicators of Ukraine's industrial and food security and assess the potential effects of organic agriculture development strategies under various war-ending scenarios by 2030.

▸ Materials and methods

To forecast the degree of fixed assets depreciation in agriculture until 2030, the ARIMAX model was used, which was built based on historical indicators from 2012 to 2021 (Sladkovska, 2023). In turn, based on the data for 2010-2024, forecasts were created for the yield of the main cereal and legume crops in general and the yield of corn in particular, using the ARMA model, and for the average annual milk yield from one cow, using ARIMAX (Sladkovska, 2023; State Statistics Service of Ukraine, n.d.). Checking the time series for stationarity using the Augmented Dickey-Fuller test (ADF) allowed for specifying the required number of differentiations (*d*) and the presence of a constant or deterministic trend in the model. The validity, reliability, and suitability of time series models for further interpretation were assessed based on stationary $R^2 > 0.5$, indicating moderate to high explanatory power, and Mean Absolute Percentage Error ($MAPE$) $\leq 10\%$, which served as an estimate of forecast accuracy. In addition, the residuals from the models had to demonstrate no statistically significant autocorrelation according to the Ljung-Box (LB) statistic, i.e., $Q_{LB}(k) < \chi^2_{crit}$ at a significance level of $\alpha = 0.05$ and $df = 1$ for k lags, the number of which was defined based on the parameters of the Autoregressive () and Moving Average () models to provide at least one degree of freedom required for the LB test. Also, in this study, the Akaike Information Criterion (AIC) was employed to select the optimal model specification.

A stationary ($d = 1$) exogenous dummy variable reflected the impact of a full-scale invasion (*warDummy*) and its completion under three different scenarios. It was used in modeling the degree of fixed assets depreciation, average annual milk yield, and the level of milk self-sufficiency. Since active hostilities began in 2022 and continued in 2025, $warDummy = 1$ was from 2022 to 2025. In 2014-2022, *warDummy* was estimated as the normalised number of civilian casualties according to the United Nations Human Rights Office of the High Commisioner (2025), characterising the intensity of the effect of russian hybrid aggression compared to 2022. Considering the considerable level of uncertainty, for 2026-2030, their forecast was carried out according to three options for the development of the security situation. The baseline scenario was defined as a linear fading of the intensity of hostilities, starting from 2026, that was, *warDummy* decreased from 1 in 2025 to 0 in 2030 in a descending arithmetic progression with a difference of 0.2. The optimistic scenario assumed the end of hostilities in 2025, which meant $warDummy = 0$ in 2026-2030. In the most unfavourable scenario, the intensity of hostilities would have continued until 2030, and therefore, $warDummy = 1$ in the same periods.

The forecasts of industrial security indicators were adjusted contingent on two strategies for the development of organic agriculture, O1 and O2, which could be implemented in Ukraine from 2026 to 2030. Due to limited data, it was assumed that the share of organic areas in 2025 remained unchanged from 2022 at 0.64% amid active hostilities (FiBL Statistics, n.d.). The O1 strategy projected a gradual rise in organic land share from 0.64% in 2025 by 0.47 p.p. annually to 3% in 2030, aligning with the Resolution of the Cabinet of Ministers of Ukraine No. 179 (2021). The O2 strategy assumed a faster linear growth of 1.98 p.p. per year, targeting 10.54% organic land by 2030 – the EU-27 average in 2022 (FiBL Statistics, n.d.). To assess the effect of expanding organic areas on fixed asset depreciation in agriculture, two cross-country regression models were developed using Eurostat (n.d.) data for EU-27 countries in 2019 and 2021. Model 1 examined the influence of capital formation in agriculture, forestry, and fisheries on fixed asset depreciation:

$$Fixed\ asset\ depreciation_i = \beta_0 + \beta_1\, Organic\ area\ share_i + \beta_2\, Capital\ formation_i + \beta_3\, D\_Country_i + \varepsilon_i, \quad (1)$$

where Organic area share – the share of organic land in the structure of the total agricultural area of country *i*; D_Country – a dummy variable, with the help of which specific anomalies for a separate country *i* were taken into account, equal to 1 if an unexplained outlier was observed (which in this study applied to Cyprus, Malta, and Slovakia); β_0 – constant; β_1, β_2, β_3 – coefficients of the cross-country regression model; ε_i – residuals.

Model 2 had the following mathematical form:

$$Fixed\ asset\ depreciation_i = \beta_0 + \beta_1\, Organic\ area\ share_i + \beta_2\, Rural\ develop\ expend_i + \beta_3\, D\_Country_i + \varepsilon_i, \quad (2)$$

where *Rural develop expend* – expenditure on development of rural areas in country *i*.

The coefficients were considered reliable if the models had moderate or high explanatory power (Adjusted $R^2 > 50\%$), demonstrated both overall *F*-significance and the significance of all its parameters that had no multicollinearity (Variance Inflation Factor (*VIF*) <5)). Although the Durbin-Watson statistic, fluctuating around 2, indicated the absence of first-order autocorrelation ($k = 1$), ε_i were additionally tested using the LB test to ensure the absence of potential higher-order autocorrelation ($k = 7$). According to the European Commission (2023), organic crop yields were 5-30% lower than conventional ones. Therefore, a stress test was conducted under the O2 strategy (2026-2030), assuming a maximum 30% yield loss to assess the impact of accelerated organic expansion on industrial security. With the total agricultural area in 2030 held constant at the 2022 level, potential cereal and corn losses were estimated. For dairy farms shifting to organic production, milk yields are typically 8-33% lower. Hence, a 33% maximum loss was assumed, with the share of organic cows increasing proportionally to organic land. Based on 3% (O1) and 10.54% (O2) organic shares in 2030, weighted average milk yield losses were calculated, assuming livestock numbers remained at 2023 levels. To assess food security, the study modeled Ukraine's self-sufficiency in milk and dairy products under war conditions and organic growth scenarios O1 and O2. Using ARIMAX models, cow numbers (2010-2023) were forecasted with a *warDummy* variable, and milk production was derived from predicted yields. Accuracy was verified by *MAPE* comparison with actual data (2011-2021). Milk consumption forecasts (2010-2030) were similarly based on cow numbers to reflect the effects of war and supply. Self-sufficiency levels were then projected through 2030 under the gradual end of hostilities and compared with historical values. The feasibility of implementing O1 and O2 was evaluated considering Ukraine's industrial and food security thresholds (Order of the Ministry of Economic Development and Trade of Ukraine No. 1277, 2013).

▸ Results

Forecasting agricultural fixed asset depreciation by 2030

To forecast the degree of fixed assets depreciation in agriculture by 2030, considering different scenarios of the intensity of hostilities, the ARIMAX (2,1,0) model was used, considering the influence of the stationary ($d=1$) exogenous variable *warDummy*. After single differentiation, the time series of the dependent variable was also determined to be stationary by type 0, since the *p*-value of the ADF test (0.04) was less than the significance level of 0.05, allowing for the rejection of the null hypothesis of a unit root presence. Since stationary $R^2 = 0.63$, the model had high explanatory power, and $MAPE = 2.17\%$ indicated high accuracy of its forecasts. Additionally, the results of checking the autocorrelation of residuals using the LB test confirmed the model adequacy. Given the number of observations in 2012-2021 ($N = 10$) and the need to involve at least one degree of freedom ($df = 1$) at $AR = 2$, $k = 3$ lags were chosen for testing autocorrelation. Since the $Q_{LB}(3) = 1.94$ was quite less than the critical value $\chi^2 = 3.84$ at the significance level $\alpha = 0.05$ and $df = 1$, and $p = 0.16 > 0.05$, the hypothesis of the absence of autocorrelation in the residuals could not be rejected. Thus, residuals that did not exceed the confidence limits were considered white noise. For these reasons, the forecast values of the degree of fixed assets depreciation in agriculture were determined to be reliable for interpretation in the context of Ukraine's economic security (Kuzyk *et al.*, 2025). The obtained values of the degree of wear and tear under the baseline scenario (gradual fading of the intensity of hostilities by 2030) demonstrated that the studied indicator of industrial security was predicted to be in an unsatisfactory state, exceeding the 45% threshold value in 2022-2026. Moreover, despite its transition to a satisfactory state due to the relative stabilisation of the security situation, the degree of fixed assets depreciation in 2030 (39.6%) still exceeded its average historical value observed in the period 2017-2021 (38.1%) (Sladkovska, 2023). In addition, the analysis of the upper confidence interval limit indicated that the indicator's path to a dangerous state in the context of industrial security was not excluded under the baseline scenario, especially in 2025-2026 (Fig. 1). Thus, the easing of the intensity of hostilities in 2026 led to the start of the restoration of the agricultural sector, the implementation of new investments and repair for damaged premises, equipment and machinery, which contributed to a reduction in the degree of wear and tear of fixed assets in agriculture

Considering the estimation of the model parameters (Table 1), the degree of depreciation in the current period (t) had a strong (0.77) statistically substantial (*p*-value = *0.04*) relationship with its value in the previous period (*t-1*). In addition, the significance of the war effect was borderline and, being on the verge of the accepted threshold (*p*-value = *0.05*), it showed that the degree of fixed assets depreciation in agriculture increased due to the beginning of hostilities by approximately 6.82 p.p. in 2022. Thus, the inclusion of *warDummy* in the ARIMAX (2,1,0) model reliably reflected the period of intensification of hostilities: the sharp increase in the degree of depreciation in 2014-2015, which was associated with the beginning of russian hybrid aggression, reproduced a similar jump, but on a much larger scale, in 2022, coinciding with the beginning of the invasion.

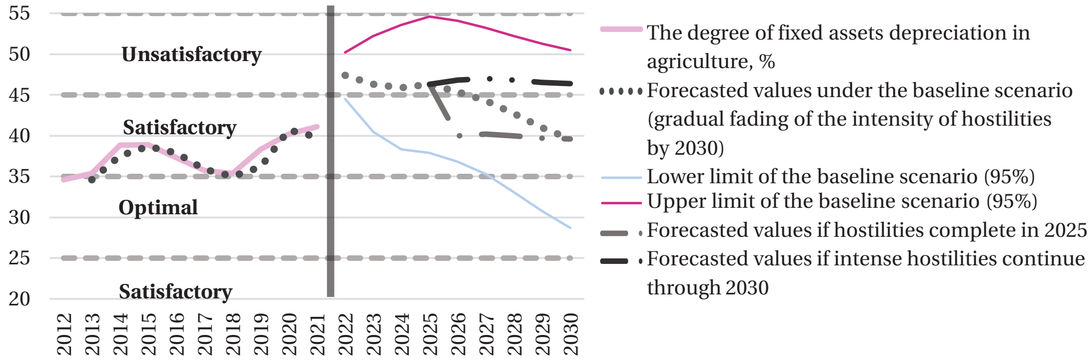

Figure 1. Agricultural fixed asset depreciation forecasts to 2030 and industrial security in 2022-2025 in Ukraine
Source: based on Ministry of Economy, Environment and Agriculture of Ukraine (n.d.)

Table 1. Parameter estimates for the ARIMAX (2,1,0) model

Variable	Estimate	Standard error	*t*-statistic	*p*-value
AR (Lag 1)	0.77	0.30	2.59	0.04
AR (Lag 2)	-0.65	0.32	-2.07	0.08
warDummy (Lag 0)	6.82	2.84	2.40	0.05

Source: developed by the author

Under the most unfavourable scenario – the intensity of military aggression that remained will until 2030 – the degree of wear and tear was in an unsatisfactory condition throughout the 2010-2024 period, reaching 47% in 2027. Thus, the long-term destruction of production capacities and the lack of financial resources for the renewal of fixed assets led to the degradation of both the material and technical equipping of the agricultural sector, which posed a threat to the country's economic security. Under the most optimistic forecast, if the hostilities ended in 2025, after peak values in 2022-2023, the degree of depreciation will begin to decrease gradually, fluctuating in 2026-2030 around the average value of 39.9%, which was higher than the average in 2012-2021 (37.57%). Among the three forecasts, this scenario was closest to the optimal indicator threshold values, indicating a massive renewal of capital in the agricultural sector, notable potential for reconstruction programmes, and the expected attraction of international investments and financial assistance in the post-war recovery period, provided that the hostilities end as soon as possible.

To quantify the impact of the share of organic land in combination with other factors on the degree of fixed assets depreciation in agriculture in the case of Ukraine implementing strategies O1 or O2, a cross-country regression model was built using data for EU-27 member states in 2019 and 2021 (Table 2). Given the summarised results, the constructed Models 1-2 were statistically significant ($p=0.00$), explaining from 51% to 65% of the variation in the dependent variable. The adequacy of the models was also confirmed by the absence of multicollinearity between the predictors ($VIF<5$) and the rejection of the hypothesis of significant autocorrelation in the residuals according to the LB test >0.05) at $k=7$ lags, the maximum number of which was determined considering $N=27$ observations. Since no problems with the correlation of factors x_i and latent time dependencies were identified, the obtained unstandardised estimates of β_j were considered reliable.

Table 2. Organic land share and agricultural asset depreciation in the EU

Model characteristic indicator/Variable	Model 1		Model 2	
Year	2019	2021	2019	2021
Key predictors (x_i)	1 – *Organic area share* (%)			
	2 – *Capital formation* (EUR 1 million) 3 – *D_Country*		2 – *Rural develop expend* (EUR 1 million) 3 – *D_Country*	
Adjusted R^2	0.57	0.51	0.65	0.62
F-statistics (*p*-value)	12.24 (0.00)	9.96 (0.00)	17.10 (0.00)	15.09 (0.00)
Durbin-Watson	2.40	1.91	2.51	2.15
Min *p* for residuals in LB test (at lag *k*)	0.07 (k=2)	0.15 (k=6)	0.09 (k=1)	0.24 (k=2)
Unstandardised β_j (*p*-value)				
β_0	7.23 (0.00)	7.13 (0.00)	6.71 (0.00)	6.49 (0.00)
β_1	-0.16 (0.00)	-0.14 (0.01)	-0.15 (0.00)	-0.12 (0.01)
β_2	0.000261 (0.01)	0.000271 (0.01)	0.002079 (0.00)	0.002247 (0.00)
β_3	-4.15 (0.00)	-4.18 (0.00)	-3.78 (0.00)	-3.68 (0.00)
Max *VIF* (for Variable)	1.13 (*D_Country*)	1.16 (*D_Country*)	1.17 (*D_Country*)	1.21 (*D_Country*)

Source: based on Eurostat (n.d.)

The impact of the *Organic area share* on *Fixed asset depreciation* in the EU-27 in 2019 and 2021 was statistically significant, negative, and relatively stable: an increase in their share by 1 p.p. was associated with an average decrease in the degree of fixed assets depreciation by 0.15 p.p., other things being equal. It could be due to investments in new means of production, more sustainable technologies, better soil care, or a lower need for intensive use of equipment and machinery. The effect of the *Capital formation* and *Rural develop* expend turned out to be positive and substantial. The statistical significance of *D_Country* for Cyprus, Malta and Slovakia indicated that *Fixed asset depreciation* in these countries was 3.7–4.2 p.p. lower compared to other EU member states, which could be due to their specific structural features or institutional programmes, in particular Malta and Cyprus are island countries with slightly different scales and conditions of agriculture, which received some of the largest payments per ha of cultivated area under the Common Agricultural Policy. According to the European Commission (2023), while the EU average for 2018-2021 was EUR 144.22 per ha, payments to Cyprus amounted to EUR 429.80 per ha and to Malta EUR 394.15 per ha, significantly exceeding the next ranked countries, such as Croatia (EUR 304.50 per ha) and Greece (EUR 290.31 per ha). Given the reliability of the parameter estimates of the regression models, the average value $\beta_1 = -0.15$ was used to adjust the primary forecast of the degree of fixed assets depreciation in Ukraine in 2026-2030 depending on the scenarios of organic area share increasing (Table 3), based on the assumption that similar relationships will be observed in Ukrainian realities against the background of European integration processes.

Table 3. Forecast adjustment of agricultural asset depreciation considering war and organics

War scenario	The target share of organic land in 2030 according to the strategy	Forecasted degree of depreciation in 2027, %	Deviation from the degree of depreciation under the baseline scenario (44.3%)
Baseline	O1: up to 3%	44.23	-0.07
	O2: up to 10.54%	44.01	-0.29
Optimistic	O1: up to 3%	40.13	-4.17
	O2: up to 10.54%	39.91	-4.39
Pessimistic	O1: up to3%	46.93	2.63
	O2: up to 10.54%	46.71	2.41

Source: developed by the author

The more ambitious development of organic production (O2) resulted in a more noticeable (compared to strategy O1), but relatively small decrease in the degree of depreciation in agriculture (-0.29 p.p.) in 2027 under the baseline scenario. It meant that although the active enlargement in the share of organic lands partially compensated for the degree of depreciation that increased as a result of the full-scale invasion, this strategy could not become the only solution to the problem of the suboptimal state of the industrial security indicator, since its negative trend was determined by both general economic factors and exogenous factors, in particular the consequences of the ongoing hostilities that began in 2014. For these reasons, in the case of the development of the safety situation under the optimistic scenario and strategy O2, the degree of fixed assets depreciation in agriculture declined the most, by 4.39 p.p. compared to the baseline forecast. It showed that the reduction of war pressure activates investments and renewal of fixed assets, bringing their degree of wear and tear closer to the upper limit of the optimal state of industrial security at 35%. In the case of the performance of the most pessimistic scenario, even moderate development of organic production under the O2 strategy did not offset the negative effect of ongoing military operations, since the degree of depreciation compared to the baseline was 2.41 p.p. higher, i.e., against the background of resource shortages, constant destruction of production capacities and agricultural infrastructure, organic agriculture development strategies were unable to counteract the large-scale degradation of the state of fixed assets in conditions of a long war.

Thus, in the context of reducing the level of fixed assets depreciation in agriculture, organic production could become one of the directions of a broader strategy for the post-war restoration of Ukraine's agricultural sector, positively affecting the state of economic security and bringing the indicator value closer to the optimal condition. However, given the small value of β_1, the development of organic agriculture did not provide a comprehensive solution for the excessive level of fixed assets depreciation and could not be recommended under the pessimistic scenario of the completion of hostilities. Moreover, it may divert limited budgetary resources necessary to support producers, who agree to implement strategies O1 and O2 from ensuring the priority needs related to national security and defence.

Forecasting crop yields to 2030 under organic strategies

The ARMA (4,0) model was used to forecast an equally important indicator of industrial security related to agriculture – the yield of the main cereal and legume crops until 2030. Unlike the degree of depreciation, when the direct impact of hostilities (*warDummy*) was considered in the ARIMAX (2,1,0) model, the dynamics of yield depend to a greater extent on natural and climatic conditions, agricultural technologies, and other factors. In addition, although the time series did not require differentiation, given the p-value $= 0.01 < 0.05$ for type 2, which were determined, when minimising the AIC, its modelling required the inclusion of the constant and trend. The constructed model, in which the values of the 2010-2024 period (t) had a marginally significant relationship with the fourth previous period (t-4), explained 72.6% of the variation of the stationary part with a *MAPE* of 9.67%, which became a satisfactory characteristic of the model quality. Since the residuals were statistically insignificant according to the LB test ($Q_{LB}(5) = 2.15$, which was less than the critical value $\chi^2 = 3.84$ at $df = 1$, and $p = 0.14 > 0.05$), the model successfully took into account all the dependencies in the time series and was used to build a reliable forecast of cereal and legume yields and its interpretation in the context of Ukraine's economic security. The deterministic trend (*p*-value = *0.00*) turned out to be a key component, as the yield of cereals, starting from a base level of 30.88 c/ha (p-value for the constant was 0.00), systematically increased by an average of 1.63 c/ha each year (Table 4). According to the forecast, the yield of cereal and leguminous crops was characterised by an upward trend – from 45.8 c/ha in 2022 to over 60 c/ha in 2028-2030. It was evidence of raised productivity of crops, soils, or improved cultivation technologies as opposed to extensive farming methods consisting of simply extending the sown areas.

Table 4. Parameter estimates for the ARMA (4,0) model

Variable	Estimate	Standard error	*t*-statistic	*p*-value
Constant	30.88	2.08	14.87	0.00
AR (Lag 1)	-0.34	0.36	-0.94	0.38
AR (Lag 2)	0.07	0.37	0.18	0.86
AR (Lag 3)	-0.11	0.43	-0.27	0.80
AR (Lag 4)	-0.62	0.31	-2.02	0.08
Trend	1.63	0.28	5.78	0.00

Notes: *Trend* variable was included in the model because the ADF test indicated that the time series was stationary around both a constant and a trend (Type 2 stationarity)
Source: developed by the author

Even though the forecast intervals expanded with distance from the last observation, which was typical for time series forecasts in the long term, the average yield level (47.4 c/ha) in 2020-2022 became the lower limit of its prognosis in 2030, indicating the potential for intensive development of the agricultural sector in the foreseeable future. However, in the context of the threshold levels of the economic security indicator presented in Order of the Ministry of Economic Development and Trade of Ukraine No. 1277 (2013), an increase in yield above 45-55 c/ha was a deterrent factor to the economic security level and, starting in 2026, the indicator finally moved from an optimal condition to a satisfactory one, ranging from 57 c/ha in 2027 to 64 c/ha in 2029. Given the upper limit of the confidence interval, which exceeded the threshold level of 75 c/ha, the forecast did not exclude the indicator being in an unsatisfactory state of industrial security starting in 2028.

According to the European Commission (2023), the yield of organic crops was 5-30% lower due to the limited use or complete ban on fertilizers, pesticides, and plant protection products. Thus, the transition to organic agriculture had a direct influence on the indicator of industrial security. To assess its impact on the state of industrial security, a stress test of the yield dynamics of cereal and leguminous crops in 2026-2030 was conducted, within the framework of which maximum yield losses were set at 30% on all organic lands under the most ambitious O2 strategy. In keeping with the results, if in 2026 the share of organic lands increased by 1.98 p.p. and amounted to 2.62%, the weighted average yield losses amounted to only 0.50 c/ha. However, in 2030, yield losses reached 1.97 c/ha if an organic production model was implemented on 10.54% of cereal and legume lands. Assuming that in 2030 the total area allocated for cereal and legume crops remained as in 2022 (12,171 thousand ha), the total harvest volume decreased by approximately 252.72 thousand tons, accounting for about 0.47% of the production volume of cereal and legume crops in 2022 (53,864 thousand tons). Since the level of grain supply in Ukraine has traditionally been high, the adjusted yield forecast also did not endanger the state of food security. Therefore, despite the potential losses, neither moderate (strategy O1) nor accelerated organic production of cereal and leguminous crops under strategy O2 created critical threats to industrial and food security. Moreover, increasing the share of organic areas to 10.54% (the O2 strategy) and maximum yield losses, on the contrary, contributed to the indicator approaching the optimal condition in the context of Ukraine's economic security, while simultaneously meeting the strategic sustainable development goals (Fig. 2).

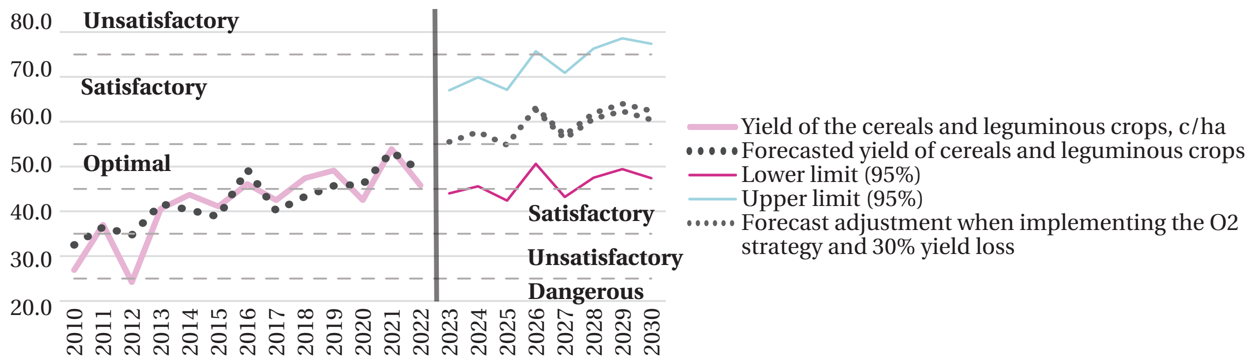

Figure 2. Crop yield forecast and stress-test adjustment to 2030
Source: based on Ministry of Economy, Environment and Agriculture of Ukraine (n.d.)

Though the dynamics of the yield of the cereal and legume crops by 2030 was not in an unsatisfactory, dangerous, or critical state, it was essential to analyse the potential risks of its component, corn yield, to the threshold values of industrial security. Moreover, the study by R. Ivanov & Yu. Hurtovyi (2023) found that its significant production volumes were not optimal, also in the context of foreign economic security. The ARMA (1,0) model was used to forecast corn yields by 2030. In this model the original time series did not have a unit root (p-value < 0.01 according to the ADF test, and the lag order according to the AIC was equal to 3, but it required considering a constant and a deterministic trend during modelling. The constructed model was characterised by the Stationary $R^2 = 0.58$, which indicated its acceptable explanatory power, and $MAPE = 8.35\%$ demonstrated even more satisfactory accuracy compared to the forecast of cereal and legume yields. Considering that the model had one autoregressive term ($AR = 1$), $k = 2$ lags were chosen for the analysis of autocorrelation of residuals so that $df = 1$. Since $Q_{LB}(2) = 1.54 < \chi^2_{crit}$ at a significance level of $\alpha = 0.05$, and $p = 0.22 > 0.05$, the model residuals did not contain any statistically substantial latent patterns, which led to the conclusion about the reliability of the forecasts and further scenario adjustments. Having estimated the parameters of the model, for corn yield the average base level was 52.80 c/ha (p-value $= 0.00$). At the same time, given the statistical significance ($p = 0.02$) of the autoregressive component, the yield up to 2030 period (t) was negatively associated, since the coefficient was (-0.67) and reflected oscillating dynamics (Table 5). In addition, corn was characterised by a stable tendency to increase yield by an average of 1.41 c/ha ($p = 0.00$), which could be associated with the positive effect of agrotechnical factors.

Table 5. Parameter estimates for the ARMA (1,0) model

Variable	Estimate	Standard error	*t*-statistic	*p*-value
Constant	52.80	2.63	20.08	0.00
AR (Lag 1)	-0.67	0.24	-2.80	0.02
Trend	1.41	0.34	4.19	0.00

Notes: *Trend* variable as included in the model because the ADF test indicated that the time series was stationary around both a constant and a trend (Type 2 stationarity)
Source: developed by the author

For corn, the yield of which in 2018-2019 and 2021 was on the verge of satisfactory and unsatisfactory state, there was a characteristic trend of increasing yield throughout the entire forecast horizon: if in 2022 it was 63.5 c/ha, by 2030 the yield grew to 82.1 c/ha, being within the range between 61.7 and 102.6 c/ha with a probability of 95%. Despite the presence of short-term cycles in its dynamics, which caused small fluctuations, the anticipated values were considerably higher compared to cereal and legume crops (on average by 18.3 c/ha in 2023-2030), since corn has historically been a higher-yielding crop (for 2010-2022, the excess was also about 20 c/ha on average). For these reasons, unlike cereal and legume crops, in the context of industrial security, corn yield, according to the forecast, was steadily in an unsatisfactory condition (>75 c/ha) starting from 2025, gradually moving towards a dangerous one. Additionally, based on the upper and lower forecast limits, it was considered reliable that, based on the threshold values, its yield was not optimal starting from 2025, and the forecast did not exclude the indicator reaching the critical level in 2029-2030 (Fig. 3).

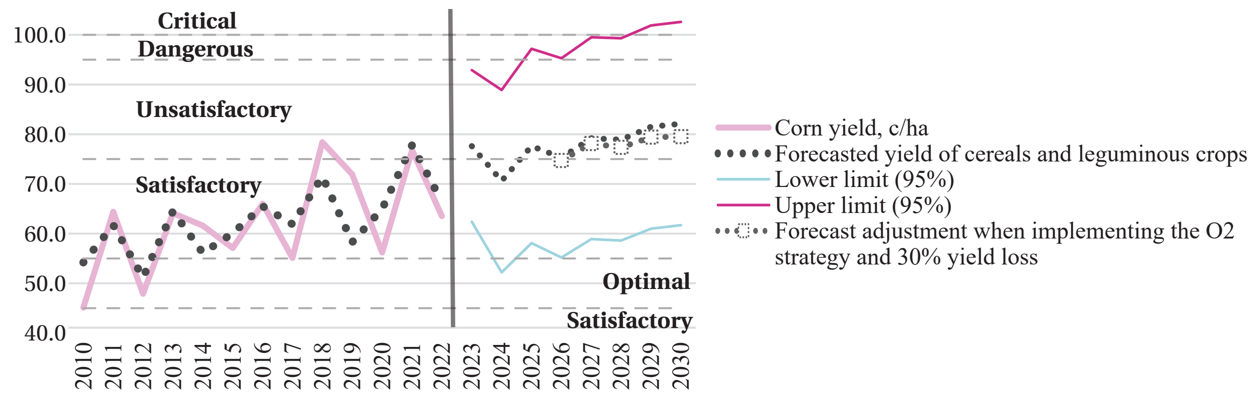

Figure 3. Forecasted corn yield and stress-test adjustment to 2030
Source: based on State Statistics Service of Ukraine (n.d.)

When assessing the consequence of the gradual transition from conventional to organic corn production on the state of industrial security, similar stress test conditions were used as for the cereal and legume crops. Simulating the maximum yield losses in 2026-2030 under the strategy of accelerated growth in the share of organic land

(O2), the results of the adjusted forecast showed that although the indicator was still in an unsatisfactory condition, it was observed to approach a satisfactory threshold value. While in 2026 the yield losses of corn amounted to only 0.59 c/ha, since about 98% of the land was still occupied by conventional agricultural production, in 2030, with organic corn cultivation on 10.54% of the areas, the losses amounted to 2.60 c/ha. If the area allocated for corn cultivation in 2030 was the same as in 2022 (4,325 thousand ha), the total harvest volume (calculated according to the O2 strategy yield forecast) declined by 118.52 thousand tons, accounting for about 0.45% of the corn production volume in 2022 (26,186.9 thousand tons) (State Statistics Service of Ukraine, n.d.). Thus, the development of organic corn production under the ambitious O2 strategy not only did not create threats to industrial security, but contributed to a lower level of its forecasted unsatisfactory condition in 2026-2030. Even though the interpretation of the results, as in the case of the yield of cereal and leguminous crops, was carried out within the framework of the Order of the Ministry of Economic Development and Trade of Ukraine No. 1277 (2013), increasing the threshold values of the indicator in the updated economic security system will most likely led to its shift to a satisfactory state, and expanding the share of organic areas for corn cultivation in the structure of agricultural land will bring its yield closer to optimal condition.

Average milk yield and industrial security, 2030

To predict the average annual milk yield per cow, which was also an indicator of the modern industrial security system, the ARIMAX (1,1,0) model was used. First-order differentiation allowed for the achievement of stationarity, since the results of the repeated ADF test (*p*-value < *0.01*) became the basis for rejecting the hypothesis of a unit root presence, although provided that a constant and a deterministic trend were present. Though milk yield was an indicator of cow productivity, which largely depended on genetics, housing conditions, completeness of feeding, and veterinary coverage, unlike other values in the time series, a negative increase in the indicator was recorded in 2022. It decreased from 5,155 kg in 2021 (Ministry of Economy, Environment and Agriculture of Ukraine, n.d.) to 5,119 kg in 2022 (State Statistics Service of Ukraine, n.d.). To assess and simulate the impact of this anomalous deviation associated with a full-scale invasion from the established trend, a stationary *warDummy* was added. Considering the dependence of the 2025 milk yield (*t*) on the indicators of the previous period (*t-1*), the model, built on data from 2010 to 2022, was characterised by high explanatory power, since stationary $R^2 = 0.78$. At the same time, the *MAPE* (0.46%) indicated a high accuracy of the milk yield forecast. Since, according to the LB test, the hypothesis of the absence of autocorrelation in the residuals could not be rejected ($Q_{LB}(2) = 1.00$ did not exceed $\chi^2_{crit.}$ under the condition of $df = 1$ at the significance level $\alpha = 0.05$, $p = 0.32 > 0.05$), the model was statistically adequate and reliable for forecasting the state of the indicator by 2030 in the context of Ukraine's economic security.

The forecast values of the average annual milk yield showed a gradual rise from 5,155.3 kg in 2023 to 5,649.3 kg in 2030 according to the baseline scenario. In agreement with the parameters of the ARIMAX model, while the average annual increase, being statistically significant (*p*-value = *0.00*), was 135.25 kg, indicating a long-term growth trend, the full-scale invasion led to an immediate and substantial reduction of 148.92 kg ($p = 0.00$) per cow (Table 6). In addition, the value of the autoregressive component (-0.75) meant that high milk yield in the current period was accompanied by lower ones in the next, and vice versa ($p = 0.02$). The statistical significance of the deterministic trend ($p = 0.03$) confirmed an additional inverse linear effect, which reduced milk yield by an average of 4.89 kg.

Table 6. Parameter estimates for the ARIMAX (1,1,0) model

Variable	Estimate	Standard error	*t*-statistic	*p*-value
Constant	135.25	14.20	9.53	0.00
AR (Lag 1)	-0.75	0.26	-2.85	0.02
Trend	-4.89	1.84	-2.66	0.03
warDummy (Lag 0)	-148.92	37.61	-3.96	0.00

Notes: *Trend* variable was included in the model because the ADF test indicated that the time series was stationary around both a constant and a trend (Type 2 stationarity)
Source: developed by the author

This forecast reflected an increase in productivity in dairy cattle breeding, coinciding with global trends in the intensive development of milk production, which are based on innovations and modern technologies to ensure feeding and keeping cattle, milking, and improving the genetic potential of the cattle breeding stock. However, despite the positive dynamics, the expected growth turned out to be insufficient for the indicator to achieve the optimal condition in the context of the current industrial security system: having crossed the threshold of an unsatisfactory state (5,000 kg) in 2020, the average annual milk yield was able to leave this state only after 8 years, given that the indicator crossed the satisfactory threshold value in 2028 (5,521.2 kg > 5,500 kg). At the same time, the current results negated the likelihood of achieving optimal yield values, since the upper forecast limit in 2030 was 5,780 kg, which was less than the optimal threshold of the current Methodological recommendations at the 6,000 kg level (Fig. 4).

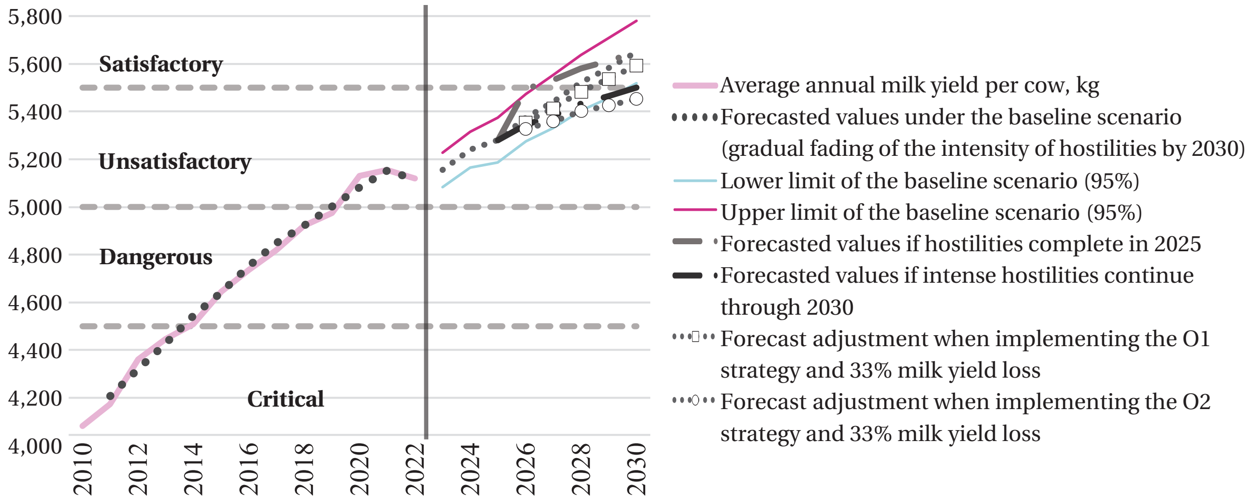

Figure 4. Milk yield forecast per cow under stress-test, 2030
Source: based on Ministry of Economy, Environment and Agriculture of Ukraine (n.d.)

According to the optimistic scenario, the average annual milk yield will increase of 4.05% in 2026, amounting to 5,493.6 kg compared to 5,279.9 kg in 2025 due to the levelling of the influence of hostilities. Moreover, under this scenario, the indicator will reach a satisfactory condition a year earlier (in 2027), in contrast to the baseline unfolding of occurrences. The pessimistic scenario revealed a gap in cow productivity, as the average milk yield will cross the threshold of a satisfactory state only in 2030, amounting to 5,500.4kg, which was 148.9 kg less than other possible alternatives. Thus, the continuation of russian aggression until 2030 will be the reason for the slowdown in the development of the agricultural sector, the average annual yield in particular, for 2-3 years in the context of Ukraine's industrial security.

As the average annual milk yield of farms that converted to organic farming was 8-33% lower than that of non-organic dairy farms (European Commission, 2023), a stress test was also conducted to assess the robustness of the industrial security indicator. By simulating the worst-case loss of milk yield of 33% on certified land used for keeping and grazing cows, increasing to 3% and 10.54% under strategies O1 and O2, respectively, the stress test results demonstrated a threat to economic security, which was a significant difference compared to cereals and corn. Given the adjusted predictions presented in Figure 4, the active implementation of organic production had a negative effect on the average annual milk yield per cow in the context of industrial security, moving the indicator away from achieving a satisfactory state. It emphasised the need for balanced development of both spheres of agriculture, because while the crop production has historically been at a high level, occupying considerable agricultural areas and dominating the export structure, husbandry, in particular dairy farming, has confirmed vulnerability to transformation processes, maintaining a long-term trend towards reducing livestock, material and resource base, and dairy production volumes.

In the case of updating the methodological thresholds of Ukraine's economic security indicator, which would be based on the experience of countries with a high level of agricultural development, where productivity was much more elevated, its predicted values in 2023-2030, which were defined as unsatisfactory and satisfactory in the context of industrial safety, may shift to the category of dangerous and unsatisfactory condition, respectively. Although the implementation of the O1 strategy postponed the achievement of a satisfactory state by a year compared to the baseline scenario, the indicator was kept within the limits of a favourable state in 2029-2030. Because of this, the O1 strategy, which had a small negative impact on the indicator (with calculated losses of weighted average productivity ranging from 19.72 kg in 2026 to 55.93 kg in 2030, when compared to the baseline forecast), could be justified by the need to achieve sustainable development goals or the orientation of the dairy production system to meet the needs of consumers on the foreign market. In contrast, the O2 strategy, which resulted in a larger gap between the average annual milk yield, caused the transition of the indicator to an unsatisfactory condition, demonstrating the adverse consequences of its performance. For these reasons, O2 could not be recommended until the milk productivity of cows raised under the conventional agricultural production system was significantly increased to compensate for the loss of milk yield resulting from compliance with organic standards.

Additionally, since in 2030 the average weighted loss of productivity per cow under the O2 strategy was 196.49 kg, which was equal to the average milk consumption per capita in Ukraine at 196 kg as of 2023 according to the Ministry of Agrarian Policy and Food of Ukraine (n.d.), it caused serious concern not only in case of industrial security condition. If the number of cows in 2030 remained as in 2023 (1,307.9 thousand heads), and the weighted average difference in productivity, when implementing the O2 strategy and a 33% loss in milk yield was 196.49 kg, the total milk losses due to the contrast in milk yield amounted to 256.994 thousand tons. Since the estimated milk losses in 2030, when implementing the O2 strategy, were equivalent to the annual milk consumption fund for 1,311.196 million Ukrainians, the transition to organic production, accompanied by a 33% reduction in cow milk productivity according to the stress test, could also pose a threat to the food security level.

Food security and dairy self-sufficiency to 2030

Due to the potential reduction in milk and dairy production volumes caused by the lower average milk yields, the likelihood of unfavourable food security conditions increased, particularly for the ratio of production and consumption for a defined food category. Given the need to consider losses in milk productivity, the modelling of this food security indicator was carried out by sequentially forecasting and aggregating its components. To calculate realistic milk production volumes by 2030, the average annual milk yield obtained in the previously ARIMAX model (1,1,0) was multiplied by the forecast values of the cow population. The prediction for the number of cows for 2024-2030 was carried out on based on historical data for 2010-2023 (State Statistics Service of Ukraine, n.d.), using the ARIMAX model (2,1,0) taking into account the exogenous variable *warDummy* ($d = 1$), which allowed for setting several scenarios of the end of hostilities by 2030, which directly affected the logistics, safety and conditions of keeping animals, their feed base and forced relocation or slaughter. Stationarity of the time series was achieved using first-order differentiation, which allowed for the rejection of the hypothesis of a unit root existence (p-value $= 0.03 < 0.05$ according to the ADF test). However, type 1 indicated the presence of a constant. Although double differentiation also confirmed stationarity, it was not advisable since it worsened the quality of the model, as evidenced by the increase in AIC by 0.29 units. Thus, the constructed model had high explanatory power (stationary $R^2 = 0.66$) and accuracy ($MAPE = 0.94\%$). In addition, the presence of autocorrelation in the residuals was checked using the LB test at $k = 3$ lags, given $N = 14$ observations and the need for $df = 1$ at $AR + MA = 2$. Since $Q_{LB}(3) = 2.11 < 3.84$ (χ^2_{crit}) at the significance level $\alpha = 0.05$, and $p = 0.15 > 0.05$, the residuals in the model did not have any unaccounted statistically substantial regularities that could cast doubt on the correctness of further calculations of milk production volumes.

Based on the model parameters estimates, the presence of a long-term trend towards a drop in the number of cows by an average of 98.23 thousand heads per year was significant (p-value $= 0.00$). Since the coefficient of the autoregressive component at lag 1 was statistically substantial ($p = 0.03$), there was a positive (0.65) relationship between the livestock of the 2010-2024 period (t) and the previous one (t-1) (Table 7). In addition, a strong negative autocorrelation with a lag of two periods was observed, given the value of $AR(2) = -0.75$, i.e., fluctuations in dynamics were observed in the time series. The beginning of a full-scale invasion (p-value was 0.03) led to a decrease in the number of cows by 73.80 thousand heads in 2022. At the same time, the dynamics of the indicator were characterised by a recovery effect, since after the initial shock associated with *warDummy*, which caused a sharp reduction in the number of cows instantly, in the following period the rate of decline slowed down, given the positive and statistically significant ($p = 0.05$) value of the numerator at lag 1.

Table 7. Parameter estimates for the ARIMAX (2,1,0) model

Variable	Estimate	Standard error	*t*-statistic	*p*-value
Constant	-98.23	7.92	-12.41	0.00
AR (Lag 1)	0.65	0.25	2.63	0.03
AR (Lag 2)	-0.75	0.22	-3.39	0.01
warDummy (Lag 0)	73.80	27.65	-2.67	0.03
warDummy (Lag 1)	79.27	33.88	2.34	0.05

Source: developed by the author

The forecast of the number of cows in Ukraine demonstrated that the weakening of the intensity of hostilities in 2026 under the baseline scenario will be an encouraging signal for households and enterprises to partially resume production activities: while in 2022-2023 the historical absolute increases were negative and amounted to (-189.0) and (-143.3) thousand heads, respectively (State Statistics Service of Ukraine, n.d.), model forecast showed it will be equal to (-69.0) and (-51.3) thousand cows in 2027-2028. However, despite the cessation of hostilities in 2030, under the baseline scenario forecast and the gradual restoration of production, the number of cows (753.5 thousand heads) remained far (-53.16%) from their number as of 2021 (1,608.5 thousand heads) (State Statistics Service of Ukraine, n.d.). Analysis of the model's upper limit of the 95% confidence interval, which was 931.61 thousand heads, gave grounds to argue that in 2030, the number of cows will be no less than 42.08% lower compared to the 2021, before the russian full-scale invasion. According to the optimistic forecast scenario, the number of cows in 2027 will exceed the corresponding indicator of the baseline scenario by 107.7 thousand heads, in 2029 – by 46.47 thousand heads. In turn, the longer events developed under the pessimistic scenario, the gap in the indicator increased because the number of cows will be lower by 45.37 thousand heads in 2027, by 106.6 thousand in 2029, compared to the baseline scenario.

By calculating the volume of milk produced as the outcome of the forecasted number of cows according to the ARIMAX model (2,1,0) and the average annual milk yield according to the ARIMAX model (1,1,0), indicators for 2011-2030 were obtained, since both time series were differentiated ($d = 1$) to achieve stationarity. Integrating both the influence of internal factors of livestock farming, which determine milk yields, and external ones, the war scenario in particular, which determined the dynamics of the livestock, the *MAPE* for historical data on milk production volumes in 2011-2022 was only 2.99%, which confirmed the adequacy of the estimated values. To forecast the volume of milk consumed in 2022-2030, an ARIMAX (1,1,1) model was built on actual data (2010-2021), which explained 58.6% of the variation in the time series with $MAPE = 1.69\%$. At the same time, moderate explanatory power and high accuracy were achieved by considering the exogenous variable, the historical (2010-2023) and predicted (2024-2030) number of cows under three scenarios, which were obtained at the previous stage. This exogenous variable enabled the indirect incorporation of both the completion of hostilities scenario, which was considered, when forecasting the number of cows by 2030, and the dependency of consumption on supply, which was directly related to the number of cows. Based on fundamental microeconomic theory, the reduction in livestock led to a decline in supply, which provoked an increase in prices, negatively affecting the volume of milk consumption. Given $AR=1$, $MA=1$, the autocorrelation test was performed at $k=3$ lags to satisfy the minimum required condition ($df=1$) for the LB test. Since $Q_{LB}(3)=0.55$, which was significantly less than $\chi^2_{кр}$, and $p=0.46>0.05$, the predictive values were reliable and could be used to interpret the indicator in the context of food security.

According to the forecast, milk and dairy product consumption began to show a gradual recovery in response to the slow decline in the intensity of hostilities, a likely increase in supply, and a slowdown in the growth of dairy prices starting in 2027, as its volumes increased by 53.8 thousand tons compared to the previous period and amounted to 7,221 thousand tons (Fig. 5). Even though the average growth rate of milk consumption in 2026-2030 at the level of 0.26% was consistent with the possible return of some Ukrainians, who left with the start of the russian full-scale invasion, as a result of the consistent improvement of the security situation, its volume in 2030, which was forecast to be 7,535.5 thousand tons, did not exceed the actual volumes of the period before the full-scale invasion (8,337.3 thousand tons), that was, the constructed model also demonstrated a general reduction in the Ukraine's population, which accordingly affected the fund of milk and dairy product consumption in the direction of its decline.

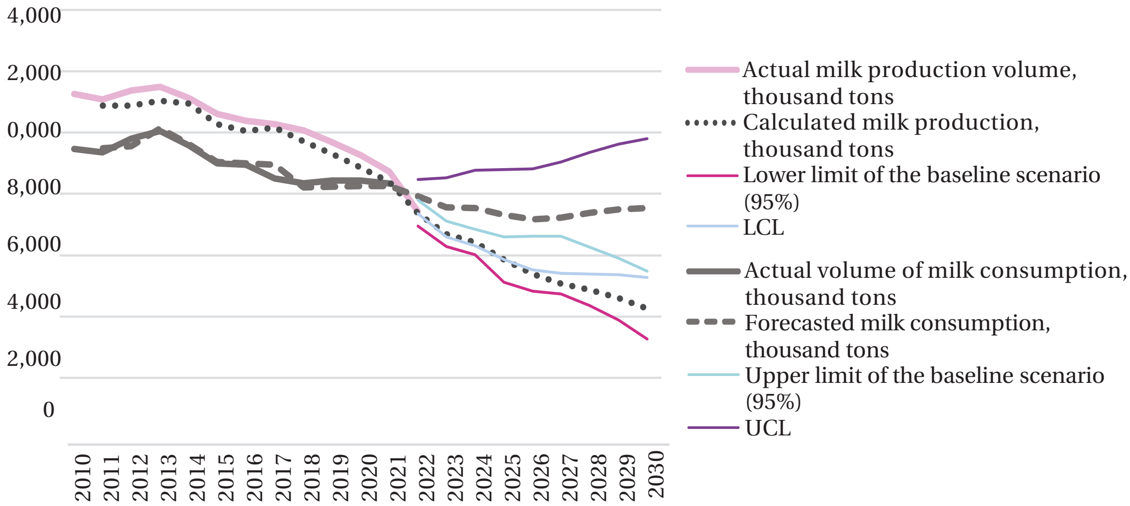

Figure 5. Forecasting of milk and dairy products production and consumption in Ukraine for 2022–2030 under the baseline war scenario
Source: based on State Statistics Service of Ukraine (n.d.)

The analysis of milk production and consumption in 2022-2030 did not exclude the possibility of meeting the population's needs with the milk produced volumes. However, it could be achieved, when production volumes were close to the upper limit, and consumption to the lower one, on the contrary. Despite the significant width of the 95% confidence intervals, in the long term, there was a weakening in food security even under such favourable conditions. While consumption volumes showed recovery, the reduction in milk production volumes was a consequence of a steady trend towards a decrease in the number of cows. Given this, the upper limit of the range for milk self-sufficiency, being 103.89% in 2030, was less than 105%. It already meant that the optimal state in the context of food security had not been achieved. Having the milk production volumes determined based on the ARIMAX (2,1,0) for the number of cows and ARIMAX (1,1,0) for the average annual milk yield, as well as the volumes of its consumption, established using the ARIMAX (1,1,1) model, it became possible to directly calculate the level of milk and dairy product self-sufficiency and its adjustment depending on the two strategies for the organic agriculture development. Keeping integrated various exogenous influences into the forecasts of the indicator components, the *MAPE* for the ratio of milk and dairy product production and consumption volumes per capita in 2011-2021 was 3.03%, which confirmed the conformity of the models to historical data and their adequacy. An analysis of the level of milk and dairy products self-sufficiency showed a noteworthy deterioration in food security as a result of the full-scale invasion: having reached a maximum in 2017 (118.2%), the indicator began to decline and in four years lost 16.5 p.p. compared to the indicated peak value, thus moving from an optimal condition to an unsatisfactory one even before the full-scale invasion, amounting to 104.5% in 2021. According to the forecast, in 2022, its level in the context of food security dropped by an additional 11.4 p.p. compared to the period before the full-scale invasion, which determined its state as unsatisfactory, which in 2023-2024 was already less than 90%, already being dangerous. In 2025 the level of milk and dairy product self-sufficiency reached a critical state in the context of food security, which only amplified, as by 2030 the indicator will reach a value of 56.49% (Fig. 6).

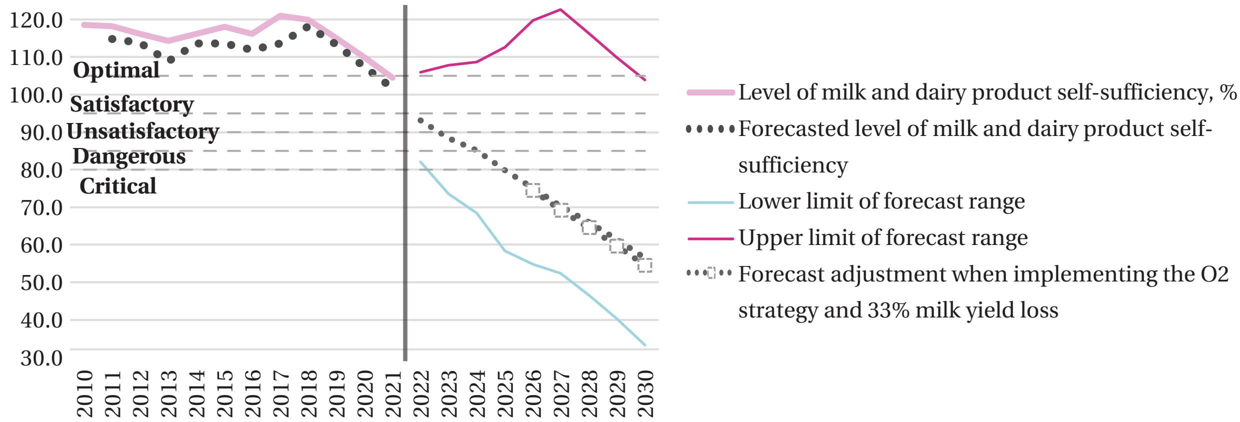

Figure 2. Forecasted dairy self-sufficiency under stress-test, 2030

Source: based on Ministry of Economy, Environment and Agriculture of Ukraine (n.d.)

Though the forecast limits were not classic 95% confidence intervals, calculated based on the upper and lower limits of the ARIMAX models for the components of the self-sufficiency level, it became the basis for evaluating possible fluctuations of the indicator. According to them, the level of milk and dairy products self-sufficiency in 2030 could be in all conditions, except for the optimal one (<105%). The obtained calculations of the level of milk and dairy products self-sufficiency were reliable if the anticipated dynamics of the reduction of the livestock population by 2030, which was based on historical data for 2010-2023, was not reversed by external factors, such as the implementation of effective state support programmes for dairy production, which will contribute to the restoration and increase of the number of cows in Ukraine. Moreover, in the ARIMAX (1,1,1) model, this exogenous variable demonstrated a statistically significant effect ($p = 0.03$) on milk consumption. A decline in the number of cows by 1 thousand heads was associated with a decrease in consumption of 5.62 tons (Table 8). That was, the model coefficient was economically justified, consistent with the average annual milk yield per cow exceeded 5,000 kg starting in 2020.

Table 8. Parameter estimates for the ARIMAX (1,1,1) model

Variable	Estimate	Standard error	*t*-statistic	*p*-value
Constant	441.36	224.42	1.97	0.09
AR (Lag 1)	-0.07	0.91	-0.08	0.94
AM (Lag 1)	-0.49	0.81	-0.60	0.57
Number of cows (Lag 0)	5.62	2.06	2.73	0.03

Source: developed by the author

The implementation of strategies, which led to an increase in the share of organic cows, has made substantial adjustments in the dynamics of the food security indicator due to lower milk productivity by 33% according to the stress test. In the case of the development of organic agriculture under the O1 strategy in 2026, the total loss of milk yield will be 19.8 thousand tons, since while the productivity of 991 thousand cows was 5,374.5 kg, which was the forecast value of the ARIMAX model (1,1,0), the productivity for 11.1 thousand organic heads (1.11% of the total livestock in 2026) will be determined at 3,600.9 kg. Along with the gradual increase in the share of organic cows to 3% by 2030, milk yield losses also will grow, reaching a maximum value of 42.14 thousand tons in 2030. It will lead to a slight increase of 0.56 p.p. in the criticality of the level of milk and dairy products self-sufficiency in 2030. Assumed that consumption per person in 2030 will recover to its average level in 2017-2021, which was 200.32 kg, with milk losses of 42.14 thousand tons, meeting food needs may become more strenuous for 210.363 thousand Ukrainians.

The implementation of the O2 strategy will lead to even more significant negative consequences, as total milk losses will range from 46.6 thousand tons in 2026 to 148.1 thousand tons in 2030 due to the enlargement in the number of organic livestock from 26.3 thousand cows (2.62%) to 79.4 thousand cows (10.54%) in the respective periods. According to the previous assumption, the milk losses in 2030 will lead to an increase in food insecurity for 739.317 thousand people, who could have consumed the produced products if the dairy farming model had remained conventional. Given the incomplete in milk and dairy products self-sufficiency throughout the entire period of 2022-2030 under the baseline scenario of the cessation of hostilities and the loss of the indicator from 1.43 p.p. in 2028 to 1.96 p.p. in 2030 compared to the baseline forecast, the transition to organic production under the O2 scenario could not be recommended, as it would worsen the state of Ukraine's food security. Since the shortage of milk and dairy products on the internal market could provoke a probable increase in imported products and prices, limiting access to milk for a considerable part of the population, the transition to organic milk production was not desirable under any of the scenarios in the context of food security. Only in the case of accelerating the productivity growth of both conventional and organic livestock and reducing the gap between them from 33% to a lower percentage of losses or breaking the negative trend towards a reduction in the number of cows, the strategy O1 for developing organic production could be justified and not move the indicator away from more favourable conditions in the context of Ukraine's food security.

Discussion

The study findings made it possible to forecast the impact of various war scenarios on key agricultural indicators of industrial security and to assess potential threats associated with the implementation of organic strategies in Ukraine against the backdrop of active hostilities. S. Gbaka & V.U. Ijirshar (2024), studying the impact of the russian invasion in Ukraine on food prices in 12 low- and middle-income countries, determined it as statistically significant, which weakened global food security in the long term. The authors estimated this effect as a dummy variable, which took the value 0 for the pre-war period (from January 2021 to February 2022) and was equal to 1 from March 2022 to April 2023. This study used a similar approach using *warDummy*, which was equal to 1 in 2022-2023. However, given that the russian hybrid aggression that began in 2014 was already causing socio-economic tension, a normalised civilian casualty rate was calculated to obtain a continuous measure of the war's impact over its entire duration, including the hybrid phase. The study by I. Rumyk (2021), modelling agricultural production per capita as the central indicator of food security, found a significant impact from the consumption of bread products and meat, but not milk. This difference could be explained by different analysis periods; specifically, the author's study might not have covered 2020-2021, when the problem of milk self-sufficiency became more evident. This study revealed a critical state of self-sufficiency in milk and dairy products, the level of which fell below the optimal state (104.5% < 105%) back in 2021 and dropped below the critical threshold (<80%) by 2025 (79.9%), indicating systemic problems in the industry exacerbated by the war. N. Shmygol *et al.* (2024) noted that for Ukraine to reach the planned 3% share of organic land, which was a strategic goal according to the National Economic Strategy until 2030, the annual growth rate must be at least +13.3%. Researchers emphasised that this share was a minimum threshold, given the progress achieved by EU countries.

The relationship between organic production and other indicators of production security was clearer. R. Ostapenko *et al.* (2020) emphasised that although lower crop yields were characteristic of organic farms with a lower economic efficiency level, wheat yields, even for organic enterprises with a higher level of development, were lower compared to conventional agriculture in 2017. Comparing organic and traditional dairy production in the EU, G. Grodkowski *et al.* (2023) found that organic milk yields were significantly lower due to energy-restricted diets and lower intake of concentrated feed. S. Portiannyk (2024), focusing on environmental safety and milk quality, recommended developing organic agriculture precisely in the post-war period, considering Ukraine's potential. This study supported this recommendation from the perspective of industrial security, demonstrating that increasing the organic cow population was possible during the post-war recovery period. Specifically, the average annual milk yield remained in a satisfactory state under both the optimistic scenario (5,531 kg in 2027) and even when implementing the O1 strategy under the baseline scenario (5,649.3 kg in 2030). The study by O. Popko (2020), which also identified opposing trends of increasing milk yields and decreasing cow numbers, predicted reaching the satisfactory level (>5,500 kg) as early as 2022 using the first-order Brown's method based on data for 1996-2018. This study accounting for the impact of external shocks (COVID-19, full-scale invasion), forecasts crossing this threshold only in 2028 (5,521 kg) using the ARIMAX (1,1,0) model (*MAPE = 0.46%*). Furthermore, the confidence interval (upper limit 5,553.1 kg) indicated that this could not have occurred earlier than 2027, thus refining previous forecasts with more actual data.

A. Ohanisian *et al.* (2022) assessed the potential of organic dairy production, forecasting an overly optimistic number of organic livestock (3,713.63 thousand heads) by 2030 under a hypothetical scenario of significant growth in investment and livestock. However, this forecast contradicted the long-term trend of declining total livestock numbers and was based on data for all livestock, not just cows. Moreover, although Ukraine does have an export-oriented agriculture, the realisation of this potential was considered unconnected with the level of milk and dairy products self-sufficiency, which, according to the results, was characterised by suboptimal conditions in the context of food security. This study predicted a significantly lower number of organic cows (79.4 thousand heads) even under the ambitious O2 strategy, which was 97.86% less than the target set by the authors. It indicated more realistic scales for the development of organic production in the context of the systemic decline in livestock numbers. The research by R. Alvarez (2021) showed that organic farming yields were 25% lower than conventional yields, and for cereals, this difference reached 30%, intensifying the debate about the organic sector's ability to meet global food needs. It aligned with the maximum value in the range of cereal yield losses (30%) used in the stress test for the industrial security indicator in this study.

The study by Z. Sun & T. Fu (2022) showed that the average cereal yield in Western Europe (1991-2020) was 68.04 c/ha, significantly exceeding modern Ukrainian levels. This study, in contrast, forecasted Ukraine reaching only 62.77 c/ha by 2028-2030. A. Grzelak (2022) showed that an increase in organic land area by one standard deviation in 2004-2019 led to an increase in the total value of assets, including fixed assets, by 0.38 standard deviations, i.e., the growth in asset value required investment in new fixed assets or modernisation of existing ones. In turn, the correlation analysis by E.J. Szymańska *et al.* (2021) found that farms with a higher value of fixed assets made larger investments, likely to modernise or replace existing assets. Based on these cascading relationships, a larger agricultural area was associated with an increase in fixed asset investments, which was often accompanied by their renewal and, consequently, a decrease in the average degree of their physical depreciation. This study empirically confirmed this indirect relationship by establishing a direct correlation: an increase in the share of organic areas by 1 p.p. led to a reduction in the degree of fixed assets depreciation by 0.15 p.p., which indicated their active renewal in organic production.

Although W. Czubak & K.P. Pawłowski (2020), which focused on the interaction of pro-investment mechanisms of the Common Agricultural Policy and sustainable economic development of farms in Central and Eastern European countries, did not verify that the beneficiaries of investment support were those farms that had a higher level of their fixed assets depreciation, however, the mandatory criterion for them was the absence of any support in the year before the investment. Given this, the lack of prior EU assistance aimed at renovation and modernisation, on the contrary, increased the likelihood that these farms had a higher degree of fixed assets depreciation. It was most likely that substantial volumes of *Capital formation* or *Rural develop expend* demonstrated positive relationships with *Fixed asset depreciation* because it was a reaction to its considerable level. Specifically, an enlargement of EUR 1 billion in these factors was associated with an increase in *Fixed asset depreciation* by 0.27 p.p. and 2.16 p.p., respectively. That was, countries where fixed asset degradation was observed were the major recipients of these financial resources. V. Aggarwal (2025), analysing the transition to organic production, emphasised that the initial investment burden related to the modernisation of fixed assets required urgent state measures of financial and technical support. This research aligned with this conclusion, recommending against the implementation of either the O1 or O2 strategies under the pessimistic scenario for the completion of hostilities. This was because the degree of depreciation remained high (47% in 2027), and additional investments would create excessive pressure on the country's limited budgetary resources, given that the state budget deficit reached almost 20% of GDP in 2022-2025 (compared to 3.63% before the invasion).

Conclusions

The study demonstrated that the state of fixed assets in Ukraine's agriculture was highly sensitive to wartime conditions. Under the baseline scenario, the depreciation level improved gradually – from an unsatisfactory 37.57% in 2012-2021 to forecast satisfactory 39.6% by 2030. The optimistic scenario showed a faster recovery, though depreciation still exceeded pre-war levels, indicating persistent post-shock effects. In contrast, the pessimistic scenario maintained an unsatisfactory depreciation rate (>45%) through 2030, signaling continued asset degradation. The expansion of organic farmland, as evidenced by EU experience, contributed to reduced asset depreciation (by 0.15 p.p.). For Ukraine, a 3% share of organic land improved the indicator by 0.07 p.p., while will reach 10.54% by 2030 led to a 0.29 p.p. improvement. Thus, organic production development could partially supported post-war recovery, though it cannot fully offset the destructive effects of prolonged hostilities.

The forecasted cereal yield exceeded the optimal range (45-55 c/ha) after 2026, will reach 79.50 c/ha by 2030. Even with losses under the O2 strategy (1.97 c/ha), the indicator approached optimal levels compared with the baseline forecast. Similarly, corn yield surpassed the unsatisfactory threshold (75 c/ha) after 2025, achieving 82.1 c/ha by 2030, and improved under O2 despite slightly higher losses (2.60 c/ha). However, milk self-sufficiency will decline under organic expansion – from 0.56 p.p. (O1) to 1.96 p.p. (O2) in 2030 – worsening an already critical condition (< 80%). Additionally, the lower average milk yield (196.49 kg less than the baseline) moved the indicator (5,493.6 kg) further from the satisfactory level (5,500 kg). Consequently, the O2 strategy cannot be recommended for maintaining food or industrial security if hostilities persist or subside only gradually. Future research should refine war impact assessment by integrating infrastructure destruction factors and modelling the potential of state support programmes to reverse negative trends, particularly the decline in livestock numbers, to strengthen Ukraine's food security.

Acknowledgements
None.

Funding
None.

Conflict of Interest
None.

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Сценарний аналіз ступеня зносу, врожайності зернових, надоїв молока у контексті економічної безпеки України

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▸ **Анотація.** Метою цього дослідження було моделювання динаміки показників промислової та продовольчої безпеки України в контексті стратегій розширення площ органічних земель і сценаріїв ведення бойових дій до 2030 року. Методологічну основу становили моделі часових рядів із урахуванням екзогенних змінних та багатофакторні моделі лінійної регресії. Встановлено, що зниження ступеня зносу основних засобів у сільському господарстві на 0,15 в.п. у результаті зростання частки органічних земель на 1 в.п. не становить загрози промисловій безпеці України, проте не може компенсувати руйнівні наслідки російсько-української війни. Визначення цільового показника у 10 % органічних площ наблизить урожайність зернових (64 ц/га) до оптимального діапазону (45-55 ц/га) за умов середньозважених втрат урожайності на рівні 1,97 ц/га у 2030 році. Урожайність кукурудзи, навіть за наявності втрат (2,60 ц/га), залишатиметься на незадовільному рівні – 75 ц/га. Хоча середньорічний надій молока, за базовим прогнозом, досягне задовільного рівня у 2028 році (5 521,2 кг > 5 000 кг), втрати урожайності (119,89 кг), пов'язані з часткою органічного поголів'я понад 10 %, унеможливлять досягнення цього рівня до 2030 року. Тому прискорений розвиток органічного молочного виробництва не може бути рекомендований за жодним із розглянутих сценаріїв. Водночас досягнення частки органічних корів у 3 % не створило загрози промисловій безпеці (за винятком песимістичного сценарію війни до 2030 року). Враховуючи критичний стан самозабезпечення молоком (<80 % починаючи з 2025 року), що стало наслідком сталого скорочення поголів'я корів, розвиток органічного молочного виробництва посилило проблему продовольчої небезпеки. Результати дослідження можуть бути використані органами виконавчої влади України для розроблення обґрунтованих стратегій переходу до органічного сільського господарства, які відповідатимуть цілям економічної безпеки

▸ **Ключові слова:** показники промислової безпеки; сценарії війни; стратегія; розвиток органічного виробництва; самозабезпечення молоком; продовольча небезпека

ЕКОНОМІКА АПК
Міжнародний науково-виробничий журнал

Том 32, № 5
2025

Відповідальний редактор:
О. Дендебера

Підписано до друку 01.10.2025
Формат 60*84/8
Ум. друк. арк. 9,4
Наклад 100 прим.

Видавництво: Національний науковий центр «Інститут аграрної економіки»
03127, вул. Героїв Оборони, 10, м. Київ, Україна
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EKONOMIKA APK

Volume 32, No. 5
2025

Managing Editor:
O. Dendebera

Signed to the print 01.10.2025
Format 60*84/8
Conventional Printed Sheet 9.4
Circulation 100 copies

Publisher: National Scientific Centre "Institute of Agrarian Economics"
03127, 10 Heroiv Oborony Str., Kyiv, Ukraine
Tel.: (+38044)258-43-21
E-mail: info@eapk.com.ua
https://eapk.com.ua/en