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Functioning of the grain market under global challenges: Theoretical and applied aspects

Abstract. The study aimed to analyse structural changes and influencing factors affecting the dynamics of agricultural markets to develop well-grounded forecasts for their progression. Methods employed included economic and statistical analysis, regression modelling, factor and correlation analysis, as well as forecasting using machine learning models. The article presented

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a comprehensive assessment of the state of the grain market in Ukraine based on data for 2024. The research focused on the analysis of production volumes, export structure, and domestic consumption of grain crops, including wheat, maize, barley, rye, oats, and others. In 2024, Ukraine's total grain harvest amounted to 54.2 million tonnes, of which 35.4 million tonnes – over 65% of the total – were exported. The main export crops remained maize (21.7 million tonnes) and wheat (11.9 million tonnes). In the consumption structure, the largest shares were allocated to feed purposes (11.7 million tonnes), food needs (5.1 million tonnes), and technical use, including seed (2.0 million tonnes). The export geography was also analysed, with particular attention to the concentration of shipments to China, Spain, Egypt, Turkey and Indonesia, which together accounted for over 56% of total exports. Special attention was given to infrastructure constraints (including a 3.8% reduction in storage capacity), transport logistics (66% by seaport, 29% by rail), and price dynamics for key crops. Average prices were recorded at 232 USD/tonne for wheat, 187 USD/tonne for maize, and 198 USD/tonne for barley. It was concluded that the increase in production and consumption is accompanied by structural changes, a growing role of technology, rising costs, and the need for an adaptive policy framework. Ukraine has the potential to maintain a 9%-10% share of global maize exports, provided infrastructure development continues and logistics are stabilised. The findings of this study may be applied to the development of agricultural policy, the optimisation of export logistics, and the formation of economic strategies in the grain production sector

Keywords: food security; agricultural policy; export potential; climate risks; logistical challenges

INTRODUCTION

The relevance of this study stems from the crucial role of the grain market in ensuring food security, driving economic growth, and supporting the export potential of agricultural countries. In the context of global demand, climate change, and logistical challenges, grain remains a strategic resource. Ukraine is among the key countries significantly shaping global trends in the production and export of grain crops. This underscores the need for a systematic analysis of production, consumption, and the influence of economic factors within the context of globalisation. The core issue addressed by this research lies in the lack of a comprehensive approach to studying the grain market, taking into account international characteristics, macroeconomic shifts, agricultural transformation, and climate-related risks. Existing data are often fragmented, access to forecasting models remains limited, and there is a need to align information on production, consumption, and pricing.

Researchers have repeatedly addressed the challenges of the grain market's functioning under conditions of economic instability. For instance, the study by V. Boyko (2022) highlights the transformation of Ukraine's agricultural market under the impact of military conflict and disruptions to supply chains. According to other researchers, the structure of agricultural production in Ukraine has required deeper institutional reforms. N.M. Rudik (2021), for instance, identified macroeconomic barriers to the development of agricultural cooperatives, which directly affected the competitiveness of the grain market. Within the scope of comparative analysis, it is also worth highlighting the findings of N.V. Brailov (2024), who examined the export positions of grain crops on the global market. The study demonstrated that in recent years, the geography of Ukraine's key grain buyers has shifted, accompanied by changes in the volume and structure of exports due to fluctuations in global prices.

In the international academic context, the technical dimension of agricultural economics is developing actively. S.B. Jones *et al.* (2022) conducted a fundamental study on dielectric methods for measuring grain moisture content, which has practical significance for the storage and transport of agricultural products. Of particular note in the field of climate impact on food systems are the findings of A. Javadi *et al.* (2023) analysed the economic consequences of climate change for food security in Iran using a computable general equilibrium (CGE) model. In the context of the biological adaptation of grain crops to climate stress, the study by B. Tadić & R. Melnik (2021) is of particular relevance. It explores self-organised critical dynamics as a key to understanding the fundamental features of complexity in physical, biological, and social networks. The authors demonstrated that the self-organisation of critical systems can be applied to enhance the resilience of agricultural ecosystems – specifically by improving plant root systems, which support more efficient absorption of water and nutrients under climatic anomalies, thereby directly contributing to production stability.

In economic discourse, increasing attention has been devoted to the theoretical grounding of effective demand as a factor shaping production volumes. In this regard, the study of P. Garegnani (2024) is significant, offering an analysis of two approaches to the formation of effective demand, based on surplus theory and intersectoral distribution. At the same time, some researchers have emphasised the financial dimension of economic transformation. Notably, L. Daumas (2024) conducted an in-depth analysis of risks associated with asset devaluation during the transition to a low-carbon development model. In the field of agricultural research, the issue of crop resilience to disease has also attracted considerable attention. The study by F. Laidig *et al.* (2021) examined advances in the breeding of winter wheat varieties with improved resistance, which helps reduce yield losses under natural infection conditions. The researchers stressed that even in traditional agroclimatic zones, the importance of genetic crop protection is increasing.

Amid climate change, growing attention has been directed towards the breeding of new crop varieties capable of withstanding extreme growing conditions. P. Langridge *et al.* (2021) argued for a strategic shift in plant breeding towards climate-resilient crops as a critical resource for food security. Their study emphasised that agricultural adaptation to climate change should begin with the scientific enhancement of seed stock. The historical and economic context of monetary policy was also explored in the research of J.S. Mill (2024), which examined the impact of currency regulation on the functioning of the banking system and market equilibrium. The author highlighted that currency stability had a direct influence on prices, exports, and the availability of raw materials, including grain crops. A notable example of structural demand adaptation is presented in the study by F. Rozi *et al.* (2023), which analysed food consumption patterns in Indonesia during the global food crisis. The authors demonstrated how, under external constraints, the population adjusted its dietary priorities – particularly concerning carbohydrate-rich crops – and how these shifts affected the domestic market. However, the integrated effects of climatic and economic factors on the grain market remain insufficiently studied. This includes cross-country comparisons of production and consumption structures, as well as long-term development scenarios that account for the challenges of globalisation.

This study aimed to conduct a comprehensive analysis of the structure and dynamics of the grain market in selected countries, taking into account economic, climatic, and logistical factors, and to develop forecast scenarios for its development under conditions of globalisation. The objectives of the research included identifying key trends in the transformation of the grain market, examining cross-country differences in the production and consumption of grain crops, and analysing the relationship between economic conditions, agricultural policy, and structural shifts in the agrarian sector.

MATERIALS AND METHODS

The scope of the study covered data for the year 2024, with particular attention given to the final stage of the 2022-2024 period, which was marked by heightened volatility due to global economic and climate-related changes. This timeframe allowed for the identification of short-term trends and cyclical fluctuations in grain production, consumption, and pricing. The methodological framework combined economic and statistical techniques with machine learning methods, including k-means and hierarchical clustering, regression analysis, and spatial analysis using open-source data. The main analytical tools included Python (with Pandas, Scikit-learn, and Matplotlib libraries), Excel, QGIS, and satellite imagery from Copernicus Open Data Hub and NASA Earth Data.

The study analysed the production, distribution, and consumption volumes of key grain crops, namely wheat, maize, and barley, as well as a group of other cereals including rye, oats, and sorghum. These crops were selected due to their central role in ensuring food and feed security, their economic significance for domestic markets and exports, and their high sensitivity to climatic and logistical changes, which makes them key indicators of the stability of the agricultural sector. Furthermore, the production, trade, and consumption data for these specific crops are well-documented in both national and international statistical sources – in particular, in databases such as FAOSTAT (n.d.), USDA (n.d.), and Eurostat (2024) – enabling objective cross-country comparisons and the development of reliable forecasts.

The study focused on a selection of countries: Ukraine, China, the USA, India, Brazil, Germany, France, Poland, Italy, and Spain. These countries were chosen for their strategic roles in the global grain market. The USA, China, and India are global leaders in terms of both production and consumption of cereals. Brazil is actively expanding its export capacity and employing advanced agrotechnologies. The European Union countries – notably Germany, France, Poland, Italy, and Spain – shape a common agricultural policy and demonstrate stable internal consumption structures. Ukraine is a key regional exporter with significant production capacity and high vulnerability to external economic conditions and logistical factors. The inclusion of these countries enabled a comprehensive analysis of the grain market at global, regional, and national levels. To analyse the structure of the grain market in Ukraine, data were sourced from the State Statistics Service of Ukraine (n.d.), agricultural analytical platforms (APK-Inform, n.d.; Latifundist, 2024), and satellite monitoring data (Sentinel-2). Factor analysis was employed to identify the key components of the market: domestic consumption, exports, and processing. Principal component analysis was used to determine the respective shares of wheat, maize, and barley in overall production and supply volumes.

To assess the influence of the macroeconomic environment on Ukraine's grain market, data from the National Bank of Ukraine (n.d.) and the International Monetary Fund (2024) were utilised. The analysis accounted for variables such as inflation rate, exchange rate, logistics costs, energy prices, government support, and the cost of fertilisers and fuel. Multiple regression was used to determine the impact of each factor on production volume and the cost of grain. Based on FAOSTAT data (n.d.), figures on grain production and consumption (in million tonnes) were collected for the selected countries. The data were normalised and aggregated by crop type. To identify trends, methods such as moving averages, linear regression, and decision trees were applied. Countries were also classified according to market type: import-dependent, self-sufficient, or export-oriented.

The grain market forecast was conducted for the following countries: China, the USA, India, Brazil, Germany, France, Poland, Italy, Spain, and Ukraine. The forecast period covered the years 2025 to 2028, aligning with the research findings that present expected figures for production, consumption, and average prices of wheat and barley in the specified countries for each year. Both machine learning and econometric models were used to forecast grain market development. Machine learning models, such as Decision Tree and Random Forest algorithms, were applied in predicting fuel costs for grain transportation (Kotenko, 2022). Econometric models, such as AGMEMOD (United Nations, 2024), were used to simulate agricultural markets, including projections for the rye market in Ukraine (Dibrova *et al.*, 2024). The data sources also included climate scenarios (Hersbach *et al.*, 2023) and price forecasts (World Bank Open Data, n.d.). To forecast wheat and barley prices while accounting for geopolitical risks and logistical barriers, time series methods such as SARIMA and GJR-GARCH-MIDAS models were employed (Dai *et al.*, 2024). These approaches made it possible to integrate economic and political factors into the forecasting process.

Logistics indicators and support measures for the agricultural sector were analysed in detail to assess the impact of military actions on Ukraine's agricultural sector. The primary sources for this analysis included official statistics from the Ministry of Agrarian Policy and Food of Ukraine (n.d.), Pro-Consulting (2024), and information from the Ukrainian State Fund (n.d.) on the implementation of government support programmes for agricultural producers. These materials enabled a comprehensive assessment of changes in logistics frameworks, the effectiveness of state compensation mechanisms (Kozlovskyi *et al.*, 2024), and the actual influence of external factors on the economic stability of Ukraine's agricultural sector.

RESULTS

The total volume of grain production in Ukraine in 2024 amounted to 54.2 million tonnes. This figure reflects the significant role of the agricultural sector in meeting both domestic and external demand for grain crops. Compared to previous years, a decline was observed: 58.6 million tonnes were harvested in 2023, and 65.0 million tonnes in 2022. This downward trend resulted from a combination of factors, including a reduction in sown areas, unfavourable weather conditions in certain regions, limited access to resources due to military operations, and rising production costs. Grain cultivation in 2024 included traditional crops such as maize, wheat and barley, as well as smaller-scale crops like rye, oats, sorghum and others (State Statistics Service of Ukraine, n.d.). The production structure indicated a continued specialisation of the agricultural sector in commercial grain production, which remained a key focus of national agricultural policy.

In 2024, grain exports remained the dominant component of the Ukrainian market. A total of 35.4 million tonnes were exported, accounting for over 65% of total production. By comparison, 38.2 million tonnes were exported in 2023 and 50.5 million tonnes in 2022. This downward trend was driven by a decline in production, logistical difficulties – particularly in the Black Sea region – and the limited operation of seaports. Despite these challenges, the export share within the market structure remained substantial, highlighting the grain sector's sustained export orientation. A total of 35.4 million tonnes were exported, accounting for over 65% of total production. This indicated a high export orientation of the grain market. The largest share of exports was maize, totalling 21.7 million tonnes, or more than 61% of all grain exports. Wheat followed with 11.9 million tonnes, representing 33.6% of total exports. Barley accounted for 1.5 million tonnes, while other grains – including rye, oats and sorghum – amounted to 0.3 million tonnes. This distribution underscored the strong concentration of exports in two key crops – maize and wheat – which were in the highest demand among international partners (Ministry of Agrarian Policy and Food of Ukraine, n.d.).

The geographical structure of grain exports in 2024 was marked by a high degree of concentration. The top five importing countries – China, Spain, Egypt, Turkey, and Indonesia – accounted for over 56% of total exports. In 2022, the largest importers were China (7.1 million tonnes), Egypt (4.2 million tonnes), Spain (3.8 million tonnes), Saudi Arabia (3.2 million tonnes), and Pakistan (2.6 million tonnes). The structure shifted slightly in 2023, with China (6.9 million tonnes), Spain (4.1 million tonnes), and Egypt (3.5 million tonnes) remaining the leading destinations, while Turkey (2.9 million tonnes) and Indonesia (2.5 million tonnes) replaced Saudi Arabia in the top five. This trend continued into 2024, with China importing 6.4 million tonnes, Spain 4.3 million tonnes, Egypt 3.8 million tonnes, Turkey 3.0 million tonnes, and Indonesia 2.7 million tonnes. These figures reflect the stability of Ukraine's key external trading partners and a noticeable shift in export focus from Middle Eastern markets to countries in Asia and Southern Europe. This reorientation was influenced by both logistical and political factors (Elevatorist, 2024a).

Domestic grain consumption in Ukraine in 2024 amounted to 18.8 million tonnes, representing approximately one-third of total grain production. By comparison, domestic consumption reached 19.4 million tonnes in 2023 and 20.1 million tonnes in 2022. This gradual downward trend was driven by both a decline in overall production volumes and reduced activity in certain sectors of the food processing industry and livestock farming. In 2024, the largest portion of domestic grain use – 11.7 million tonnes – was allocated for animal feed, highlighting the vital role of grain in supporting the livestock sector. In 2023 and 2022, these figures were 12.2 million tonnes and 13.0 million tonnes, respectively. Grain allocated for food purposes in 2024 totalled

5.1 million tonnes, comparable to the 2023 figure of 5.2 million tonnes but slightly lower than the 5.4 million tonnes recorded in 2022. The remainder – approximately 2.0 million tonnes each year – was used for seed, technical needs, and losses.

This distribution confirmed a stable structure of domestic consumption, characterised by the dominance of feed use and a gradual decline in volumes in line with the overall reduction in production. The grain processing industry comprised approximately 1,180 enterprises engaged in both primary and advanced processing. The sector was largely made up of small and medium-sized producers operating mainly at the regional level. Between 2022 and 2024, the ratio of exports to domestic sales of processed grain products remained relatively stable: around 63% was exported, while 37% was used on the domestic market. This indicated a high dependence of the processing sector on external demand, particularly for flour, groats, compound feed, and other grain-based products (USDA, n.d.). The grain storage infrastructure included around 510 facilities with a combined capacity of 38.5 million tonnes. Despite the relatively high figures, the system remained under pressure, as some storage facilities were damaged by hostilities – especially in the southern and eastern regions. A 3.8% reduction in available capacity placed additional strain on operational facilities, forcing producers to accelerate the sale of grain or seek alternative storage arrangements (Elevatorist, 2024b).

Logistics played a crucial role in supporting grain exports. Maritime ports accounted for 66% of grain shipments. However, security risks in the Black Sea region prompted exporters to make greater use of rail corridors to EU countries, which handled 29% of export volumes. Road transport remained a supplementary channel, accounting for approximately 5%, and was primarily used in border regions or for short-haul routes. Price conditions remained stable. The average export price for wheat was 232 USD per tonne, maize sold for 187 USD, and barley for 198 USD (UkrAgroConsult, n.d.). These price levels enabled the agricultural sector to secure foreign currency revenues and maintain the profitability of grain cultivation. Prices were shaped by global market quotations, demand from key importers, transportation costs, and competition from other major exporters (Table 1).

Table 1. Structure of the Ukrainian grain market (2022-2024)

Indicator	Unit of measurement	2022	2023	2024	Notes
Total grain production	million tonnes	65.0	58.6	54.2	Decline compared to 2022 due to adverse weather conditions and reduced sown areas
Grain exports (total)	million tonnes	50.5	38.2	35.4	65.3% of production
Wheat	million tonnes	16.4	13.2	11.9	33.6% of exports
Maize	million tonnes	30.0	22.3	21.7	61.3% of exports
Barley	million tonnes	2.6	1.7	1.5	4.2% of exports
Other (rye, oats, sorghum, etc.)	million tonnes	0.5	0.4	0.3	~0.9% of exports
Main importing countries	–	–			Share of total exports
China	million tonnes	7.1	6.9	6.4	18.1%
Spain	million tonnes	3.8	4.1	4.3	12.1%
Egypt	million tonnes	4.2	3.5	3.8	10.7%
Turkey	million tonnes	2.4	2.9	3.0	8.5%
Indonesia	million tonnes	2.1	2.5	2.7	7.6%
Domestic consumption (total)	million tonnes	20.1	19.4	18.8	34.7% of production
For animal feed	million tonnes	13.0	12.2	11.7	62% of domestic consumption
For food purposes	million tonnes	5.4	5.2	5.1	27%
For seed, losses, and technical needs	million tonnes	1.7	2.0	2.0	11%
Processing industry	–	–			–
Number of enterprises	units	1,175.0	1,180.0	1,180.0	Mainly flour, groats, and pasta production

Table 1, Continued

Indicator	Unit of measurement	2022	2023	2024	Notes
Share of output exported	%	63.0	63.0	63.0	Remaining share is used domestically
Storage infrastructure	–	–			
Number of grain storage facilities	units	525.0	515.0	510.0	Some were damaged due to hostilities
Total storage capacity	million tonnes	40.0	39.5	38.5	Decline of 3.8% due to capacity losses
Average grain selling prices	USD/tonne	–			Influenced by global market conditions
Wheat	USD/tonne	245.0	238.0	232.0	Annual average
Maize	USD/tonne	198.0	192.0	187.0	Annual average
Barley	USD/tonne	210.0	204.0	198.0	Annual average
Main export logistics routes	–	–			Share of shipments
Seaports (Odesa, Chornomorsk, etc.)	%	72.0	69.0	66.0	Decrease due to risks in the Black Sea region
Rail corridors to the EU	%	24.0	27.0	29.0	Increased role of land routes
Road transport	%	4.0	4.0	5.0	Used mainly for border deliveries

Source: developed by the authors based on USDA (n.d.)

In summary, the structure of Ukraine's grain market in 2024 was characterised by a high reliance on exports, relative stability in domestic consumption, and the growing significance of the processing sector. Logistical challenges, infrastructure constraints, and price fluctuations shaped current market dynamics, while sustained international demand continued to offer potential for further development. One of the key economic factors in 2024 was the cost of grain production, which rose on average by 12.4% compared with the beginning of the year. In 2023, the increase was 9.7%, and in 2022 – 7.5%, indicating a general upward trend in production costs. The main expenditure items included mineral fertilisers, fuel, seeds, crop protection products, wages, and land lease payments. The price of diesel fuel, essential for harvesting and transport, averaged 1.20 EUR per litre in 2022, 1.40 EUR per litre in 2023, and 1.50 EUR – 1.60 EUR per litre in 2024, significantly contributing to the rise in logistical costs. Additional pressure was caused by increasing freight rail tariffs: these rose by 8% in 2022, 12% in 2023, and 18% in 2024 (Agronews, 2024).

Against the backdrop of high production costs, the profitability of grain cultivation in Ukraine was heavily dependent on global market prices. The average export price of wheat stood at 245 USD per tonne in 2022, 238 USD per tonne in 2023, and 232 USD per tonne in 2024. For maize, prices declined from 198 USD per tonne in 2022 to 192 USD per tonne in 2023 and 187 USD per tonne in 2024. Barley was priced at 210 USD, 204 USD, and 198 USD per tonne, respectively. When the price-to-cost ratio was favourable, the profitability of wheat production was estimated at 10%-14% in 2022, 9%-11% in 2023, and 8%-12% in 2024. For maize, returns were 8%-10%, 7%-9%, and 6%9%, respectively, which reduced the incentive to expand the area under cultivation. Another critical factor was the exchange rate. The average rate was 29.3 UAH per USD in 2022, 36.6 UAH per USD in 2023, and 38.2 UAH per USD in 2024. This had a substantial impact on export earnings, which accounted for up to 40% of total profits in the agricultural sector. At the same time, exchange rate volatility throughout the year created uncertainty in income forecasts and affected the cost of imported inputs (Economic Pravda, 2024).

Investment activity in the grain sector remained restrained. In 2022, investment in grain production totalled approximately 18.4 billion UAH, decreasing to 16.7 billion UAH in 2023 and 15.1 billion UAH in 2024, reflecting an annual decline of 9.3%. Large agroholdings accounted for the majority of investment, while small and medium-sized farms largely limited spending to the modernisation of core machinery. Bank lending was more accessible in 2022, with an average interest rate of 17.9%; however, this rose to 20.3% in 2023 and reached 22.5% annually in 2024. Crop insurance remained underdeveloped: only 6% of cultivated land was insured in 2022, 6.5% in 2023, and 7% in 2024, primarily through international programmes. The high cost of policies, lack of government support, and bureaucratic complexity constrained the wider adoption of this risk management tool (National Bank of Ukraine, n.d.). Inflation also had a notable impact on the agricultural sector: it stood at 20.2% in 2022, 14.8% in 2023, and 11.2% in 2024. Due to infrastructure damage, storage capacity declined by 1.2 million tonnes in 2022, by a further 1.0 million tonnes in 2023, and by another 1.5 million tonnes in 2024. This led to an increase in storage service costs by 12% in 2022, 15% in 2023, and between 14% and 18% in 2024. As a result, many farmers were forced to sell their grain immediately after harvest (Debet, n.d.)

The export logistics situation between 2022 and 2024 remained unstable. In 2022, maritime ports accounted for 72% of grain transport, decreasing to 69% in 2023 and further to 66% in 2024. Conversely, the share of rail deliveries to the EU rose from 24% in 2022 to 27% in 2023 and reached 29% in 2024. As a result of longer routes, the average freight cost increased from 18 USD per tonne in 2022 to 22 USD in 2023 and 25 USD in 2024. The average duration of the logistics cycle also rose, from 12 days in 2022 to 16 days in 2023 and 18 days in 2024 (APK-Inform, 2024). Due to changes in export routes, the average logistics cycle time increased from 12 to 18 days. These changes in export routes led to longer delivery times, adversely affecting the timely fulfilment of international trade contracts (Table 2).

Table 2. Key economic factors influencing Ukraine's grain market (2022-2024)

Economic factor	Unit of measurement	2022	2023	2024	Impact on economic indicators
Cost of wheat production	UAH/tonne	5,700.0	6,050.0	6,400	Reduced profitability compared to 2022
Cost of maize production	UAH/tonne	6,200.0	6,600.0	6,900	High dependence on fuel
Average export price of wheat	USD/tonne	245.0	238.0	232	Positive, but limited impact
Average export price of maize	UAH/USD	198.0	192.0	187	Moderate impact
Exchange rate	%	29.3	36.6	38.2	Affects export earnings
Average inflation rate	billion UAH	20.2	14.8	11.2	Reduces purchasing power
Investment in the grain sector	%	18.4	16.7	15.1	Low activity among SMEs
Agricultural sector lending rate	%	17.9	20.3	22.5	Limited access to finance
Share of insured crop area	%	6.0	6.5	7	High risks of crop loss
Increase in storage costs	%	12.0	15.0	14-18	Forced early sales
Share of railway logistics	%	24.0	27.0	29	Route changes, rising costs
Average logistics duration	days	12.0	16.0	18	Delivery delays

Source: developed by the authors based on APK-Inform (2024)

In 2024, economic factors created a challenging environment for the functioning of Ukraine's grain market. High production costs, inflation, exchange rate fluctuations, rising logistics expenses, and declining investment activity constrained development opportunities. Despite stable export demand, domestic economic conditions remained difficult and required a comprehensive approach from the government, businesses, and international partners. Global grain production in 2024 reached approximately 2,855 million tonnes, demonstrating steady growth driven by advancements in agricultural technologies, expansion of sown areas, and improvements in infrastructure across leading agricultural countries. The largest producers remained China, India, the USA, Brazil, Argentina, and European Union countries such as Germany, France, Poland, Italy, and Spain, collectively accounting for over 70% of the world's grain output. The widespread adoption of precision farming technologies, efficient resource use, state support, and international investment played a decisive role in enhancing production efficiency. Global grain consumption reached 2,840 million tonnes, only slightly below total output. The main consumers were countries with large populations, well-developed food processing industries, and advanced livestock sectors. Grain was used for food production, animal feed, and as an industrial raw material – particularly in the manufacture of biofuels, starch, and alcohol. The rise in consumption was driven not only by demographic trends but also by structural shifts in food supply chains in developing countries (APK-Inform, 2024).

Ukraine maintained its position as one of the leading grain exporters, ensuring consistent supplies to countries in the Middle East, North Africa, Asia, and Europe. In 2024, national grain production totalled 54.2 million tonnes, with domestic consumption amounting to 18.8 million tonnes. As a result, over 65% of total production was export-oriented. The primary crops were maize, wheat, and barley, with maize leading in export volumes, while wheat was more commonly consumed on the domestic market (Latifundist, 2024). Within the structure of domestic grain consumption in Ukraine, approximately 11.7 million tonnes were used for animal feed, reflecting the central role of grain in supporting the livestock sector. A further 5.1 million tonnes were consumed by the food industry for the production of flour, cereals, bread, and pasta. The remainder was used for seed, losses, and industrial processing. Regional consumption patterns showed a higher share of grain used for food purposes in western regions, while central and southern areas focused more heavily on feed production (International Monetary Fund, 2024).

Grain production in Ukraine remained dependent on a range of variable factors. Weather conditions, fertiliser prices, fuel costs, and logistics services played a key role. Economic policy also had a significant impact, including the level of taxation, access to finance, the investment climate, and state support for agricultural producers. In 2024, investment in agriculture was insufficient to enable a full-scale renewal of machinery, modernisation of storage infrastructure, or productivity improvements in small and medium-sized farms. Despite these challenges, Ukraine's grain sector remained competitive. The country's share in the global maize market held steady at around 10%, while wheat was exported to dozens of countries with varying standards and quality requirements. Ensuring a high level of phytosanitary control, certification, and product traceability became essential to maintaining access to demanding markets, particularly in Europe (Fig. 1).

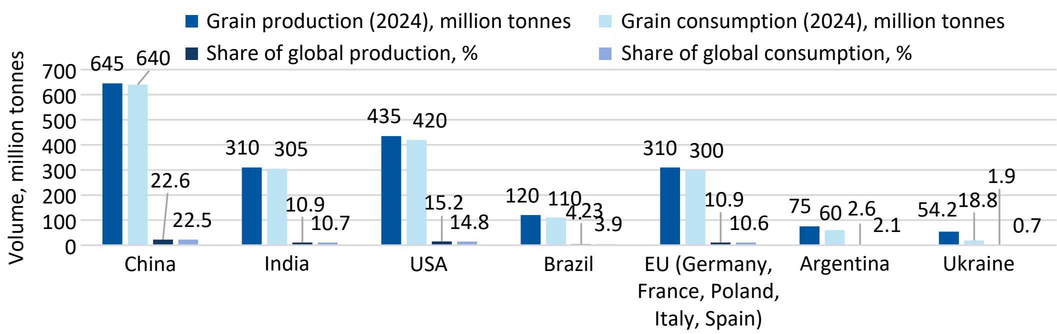

Figure 1. Grain production and consumption by country (2024)
Source: developed by the authors based on FAOSTAT (n.d.)

In summary, the structure of grain production and consumption in both the global and Ukrainian contexts remained dynamic in 2024 – flexible in the face of change and sensitive to global economic processes. Ukraine continued to play a strategic role in ensuring international food security while also maintaining domestic food stability through a flexible consumption structure and the growing potential of its processing sector. In 2024, the grain markets in countries such as China, the USA, India, Brazil, Germany, France, Poland, Italy, Spain, and Ukraine remained dynamic, adaptable to change, and responsive to economic challenges. Ukraine played a key strategic role in securing food supplies, supporting stable domestic consumption, and developing both its export and processing capacities. From 2025 onwards, further growth in grain production is projected in these countries. Forecasted production volumes may reach 2,890 million tonnes in 2025, 2,925 million tonnes in 2026, 2,960 million tonnes in 2027, and 2,995 million tonnes in 2028. This growth is expected to be driven by the active adoption of innovations, the expansion of cultivated areas in Africa and Latin America, and the modernisation of logistics infrastructure in leading agricultural countries. Consumption is likewise expected to rise to 2,875 million tonnes in 2025, 2,910 million tonnes in 2026, 2,945 million tonnes in 2027, and 2,980 million tonnes in 2028 (Bogonos *et al*., 2024).

The greatest contribution to global grain production is expected to come from China, the USA, India, Brazil, and the European Union – particularly Germany, France, Poland, Italy and Spain. In China, production may stabilise at over 645 million tonnes, with consumption reaching up to 660 million tonnes. The USA could achieve volumes of up to 450 million tonnes, supported by the widespread adoption of precision agriculture. India, through its robust agricultural programmes, is projected to maintain production at 310-320 million tonnes. In Brazil, the development of irrigation systems and biotechnologies is likely to boost output to around 130 million tonnes. In Germany, France, Poland, Italy and Spain, total production may reach 318 million tonnes by 2028 (United Nations, 2024).

The structure of grain consumption is shifting increasingly towards feed use, particularly in China, the USA, India and Indonesia. The share of feed grain in total consumption may exceed 50% by 2028. Demand is also expected to rise in the energy sector, especially for bioethanol production in the USA, Brazil and EU countries. Price dynamics are likewise projected to follow an upward trend. The average global price of wheat is forecast to reach 248 USD/tonne in 2025, 255 USD/tonne in 2026, 262 USD/tonne in 2027 and 268 USD/tonne in 2028. Maize prices are expected to reach 193 USD/tonne, 199 USD/tonne, 203 USD/tonne and 208 USD/tonne, respectively. The main drivers of this price growth are anticipated to be logistics costs, energy markets, and geopolitical risks (World Bank Open Data, n.d.).

Between 2025 and 2028, Ukraine is expected to maintain grain production within the range of 55-60 million tonnes. The export potential of maize may reach up to 25 million tonnes annually, with key markets including China, Spain, Italy, Egypt and Indonesia. Ukraine's share in global maize exports could account for 9%-10%. At the same time, domestic processing of bioethanol and flourbased products is expected to expand (Mind, 2024). By 2028, over 60% of large agricultural enterprises in the USA, Brazil, Germany and France may adopt fully automated field management systems, significantly increasing production efficiency. In Ukraine, the level of digitalisation is projected to remain at around 25%-30%, with potential for growth supported by both state and international initiatives (Table 3).

Table 3. Forecasts for the development of the grain market under globalisation (2025-2028)

Year	Country	Production (million tonnes)	Consumption (million tonnes)	Average wheat price (USD/tonne)	Average barley price (USD/tonne)
2025	China	648	645	248	220
2026	China	652	650	255	226
2027	China	656	655	262	232
2028	China	660	660	268	238
2025	USA	438	422	248	220
2026	USA	442	425	255	226

Table 3, Continued

Year	Country	Production (million tonnes)	Consumption (million tonnes)	Average wheat price (USD/tonne)	Average barley price (USD/tonne)
2027	USA	446	428	262	232
2028	USA	450	430	268	238
2025	India	312	308	248	220
2026	India	315	311	255	226
2027	India	318	314	262	232
2028	India	320	317	268	238
2025	Brazil	122	112	248	220
2026	Brazil	125	114	255	226
2027	Brazil	128	116	262	232
2028	Brazil	130	118	268	238
2025	Germany, France, Poland, Italy, Spain	312	302	248	220
2026	Germany, France, Poland, Italy, Spain	314	304	255	226
2027	Germany, France, Poland, Italy, Spain	316	306	262	232
2028	Germany, France, Poland, Italy, Spain	318	308	268	238
2025	Ukraine	56.0	19.0	248	220
2026	Ukraine	57.0	19.5	255	226
2027	Ukraine	58.0	20.0	262	232
2028	Ukraine	60.0	20.5	268	238

Source: developed by the authors based on H. Hersbach *et al.* (2023), estimates based on GJR-GARCH-MIDAS time series modelling

Thus, between 2025 and 2028, the functioning of the grain market in countries such as China, the USA, India, Brazil, Germany, France, Poland, Italy, Spain and Ukraine is likely to be shaped by a combination of interconnected economic and structural factors. Gradual increases in production costs, fluctuations in energy prices, logistical challenges, and global inflationary trends are expected to create a complex environment for sustainable development. At the same time, technological innovations, growing demand for bioenergy feedstocks, rising feed grain consumption and the intensification of international trade will support positive market dynamics. Despite challenging domestic conditions, most countries are projected to maintain their production capacities through modernisation, supportive agricultural policies and diversification of export markets.

In 2022, grain exports through the "grain corridor" totalled 21.8 million tonnes, accounting for over 53% of total exports. This underscored the critical role of maritime transport in grain logistics, even amid wartime challenges. However, in 2023 and 2024, this figure declined steadily, falling to 11.2 million tonnes in 2023 and 9.4 million tonnes in 2024. The decline in maritime transport volumes was driven by heightened risks to shipping in the Black Sea region, as well as increased vessel idle times in ports due to stricter inspection and security procedures. In particular, the average vessel layover increased from 21 days in 2022 to 29 days in 2024. This reflected rising logistical costs and reduced efficiency of transport operations, which negatively affected the competitiveness of Ukrainian grain on international markets (Food and Agriculture..., 2024). Against the backdrop of declining maritime shipments, the share of rail transport in total grain exports increased. While in 2022 rail accounted for only 27.3% of total grain exports, by 2024 this figure had risen to 35.2%. This growth was a necessary response to the maritime blockade and security threats to sea routes. However, rail transport faced its own limitations, including insufficient capacity and high logistical costs, which further worsened the economic performance of agricultural producers (Pro-Consulting..., 2024).

An analysis of the effectiveness of state support programmes for farmers reveals a growing number of compensation applications. In 2022, 58.2 thousand applications were submitted; this rose to 61 thousand in 2023 and reached 65.8 thousand in 2024. However, the approval rate for these applications steadily declined, from 44.6% in 2022 to just 30.5% in 2024. This trend indicates increasing bureaucratic barriers, budgetary constraints, and limited flexibility in the review and decision-making processes. As a result, despite the rising number of applications, the actual amount of compensation disbursed decreased from 3.2 billion UAH in 2023 to 2.7 billion UAH in 2024 (Ukrainian State Fund, n.d.). International support for the agricultural sector also played a significant role. In 2022, it amounted to 6.7 billion UAH, rose substantially to 12.4 billion UAH in 2023, but then declined again to 10.9 billion UAH in 2024. These fluctuations reflect the instability of external funding, partly driven by changing political conditions and a shift in donor priorities. An important social aspect of the support programmes was the growing share of smallholder farmers among compensation recipients. In 2022, small farms accounted for 61% of recipients, rising to 69% by 2024. This was a positive indicator in terms of providing social support to the most vulnerable participants in the agricultural sector, particularly those most affected by the war and economic losses (Table 4).

Table 4. Logistics and agricultural support indicators (2022-2024)

Indicator	2022	2023	2024
Grain exports via the "grain corridor", million tonnes	21.8	11.2	9.4
Share of maritime transport in total exports, %	53.1	42.8	39.5
Share of rail transport in total exports, %	27.3	31.5	35.2
Average vessel delay time in the corridor, days	21.0	27.0	29.0
Number of compensation applications, thousand	58.2	61.0	65.8
Approved applications, %	44.6	34.1	30.5
Total compensation payments, billion UAH	1.9	3.2	2.7
International support (UAH equivalent), billion	6.7	12.4	10.9
Share of smallholder farmers among recipients, %	61.0	67.0	69.0

Source: developed by the authors based on Ukrainian State Fund (n.d.), Ministry of Agrarian Policy and Food of Ukraine (n.d.)

Overall, the analysis of data from 2022 to 2024 demonstrated that Ukraine's agricultural sector suffered significant losses due to the war and logistical constraints. On the one hand, the decline in maritime exports and the growth of rail transport indicated serious structural changes in logistics. On the other hand, although state compensation programmes played an important role in supporting farmers, a range of administrative and financial challenges prevented them from fully offsetting the losses incurred. Consequently, the sector's further development requires stronger state support policies, in particular through optimising compensation procedures, stabilising international aid, and developing alternative export corridors for Ukrainian grain.

DISCUSSION

The findings indicate that the grain market remains highly dynamic in the world's leading countries, with China, the USA, India, Brazil, EU member states, and Ukraine playing particularly significant roles. Projected growth in production, reaching up to 2,995 million tonnes by 2028, is likely to be accompanied by an almost proportional increase in consumption, reflecting stable global demand. At the same time, the share of grain used for feed is expected to continue rising, prompting structural shifts in domestic markets across many countries. Ukraine's strengthening export potential, despite logistical constraints, highlights its adaptability; however, this also underscores the need for infrastructure modernisation and sustained government support. In the EU and the USA, there is a clear trend towards increased technological integration, particularly the adoption of automated systems in large-scale agricultural enterprises. Alongside these developments, the growing impact of climate-related challenges – such as yield fluctuations and drought risk – emphasises the need for adaptive crop varieties and adjustments in agronomic practices.

In particular, J. Małecki *et al.* (2021) and T. Qiu & B. Luo (2021) focused on specific aspects of agricultural production that partially align with the findings of this study. J. Małecki *et al.* examined the functional properties of proteins in cereal products and their potential applications in modern food systems. While this approach is valuable for assessing grain quality, it does not consider the broader economic or market context addressed in the present study. By contrast, T. Qiu & B. Luo concentrated on the impact of agromechanisation in small-scale farming in China. Their conclusions highlight the importance of technological factors in improving crop yields, which partly corresponds with the findings of this research. However, in the present approach, technological advancement is viewed more broadly – not merely at the level of farming practices, but as part of the wider transformation of the agricultural sector under the influence of global climate and economic changes.

R. Anibaldi *et al.* (2021) also examined grain markets from the perspective of institutional and logistical efficiency. Their focus was on the barriers to implementing sustainable agricultural practices, particularly regarding farmer motivation and support systems. While their conclusions are important for understanding the socio-economic dimensions of the sector, the study is largely descriptive and does not include a quantitative analysis of production or consumption indicators. X. Peng *et al.* (2022) developed a multi-channel information management model for the rice supply chain. Although their approach is logistically effective, it is limited to a single crop and region, without incorporating forecasting dynamics, climate-related risks, or global pricing trends. In contrast, the present study integrates institutional, logistical, economic, and agroclimatic approaches within a unified framework of analysis and scenario modelling. A. Dibrova *et al.* (2024) explored the functioning of the rye market as a niche grain crop in the context of rising mineral fertiliser costs. Their research focused on forecasting and modelling production and price dynamics – issues highly relevant in light of global challenges such as economic instability and the agricultural sector's reliance on external resources. The authors highlighted the importance of adapting agricultural policy to changes in the fertiliser market, given its direct impact on the profitability of grain cultivation.

Researchers S.R. Tushar *et al.* (2023) addressed issues related to grain storage resilience and the circular economy in agricultural supply chains. Their study examined factors influencing the stability of grain storage – particularly moisture levels, temperature, ventilation, and their impact on food security. This presents a valuable addition to the technological dimension, which is also considered in the present analysis. However, the research by S.R. Tushar *et al.* does not explore forecasted changes in market structure or global demand dynamics. In turn, A.A. Dossa *et al.* (2022) focused on the spread of the circular economy in the wheat supply chain in the United Kingdom. While their analysis is relevant in the context of sustainable development, it remains geographically and conceptually limited. By contrast, the present study offers a more comprehensive approach – encompassing a broader range of countries and crops, and integrating economic, environmental, logistical, and forecasting components within a unified interdisciplinary framework.

Researchers T. Mukherjee *et al.* (2023) proposed approaches that enhance the overall understanding of analytical methods in the agricultural and related sectors. Their study focused on managing grain microstructure in the context of additive manufacturing, emphasising the precision of material control. Although the research concerned metals, the principle of controlling quality parameters holds cross-sectoral relevance for agricultural production, particularly in grain storage and processing. Meanwhile, S. von Cramon-Taubadel & B.K. Goodwin (2021) conducted a comprehensive analysis of price transmission in agricultural markets, focusing on responses to global price shocks. Despite the high level of analytical depth, their study is confined to price-related factors. In contrast, the present research incorporates a broader set of variables – from agroclimatic conditions to logistical constraints and geoeconomic risks – offering a more integrated and multifaceted factor analysis.

E. Tadele & T. Hibistu (2021) examined transformational processes within national agri-food systems, with a particular focus on internal development factors. Their study explored the use of teff in Ethiopia's agricultural sector, highlighting its nutritional value, cultural significance, and stable role in consumer diets. The research demonstrated a link between local practices and systemic food security; however, it lacked macroeconomic or forward-looking analysis. Meanwhile, Y. Liu *et al*. (2023) investigated the impact of financial liberalisation on productivity growth in China's agricultural sector, employing a mechanistic model that accounted for the quality of land, labour, and capital. Despite the analytical depth of both studies, each remained limited to a single national context and did not incorporate cross-country comparisons or assessments of global trends – key elements in the present research aimed at constructing a comprehensive picture of the market up to 2028.

At the same time, S. Das *et al.* (2023) and P. Khatri *et al.* (2024) presented a multidimensional perspective on agricultural risks, focusing on the interconnections between environmental, economic and social factors. P. Khatri *et al.* examined the nature of compound risks in agricultural production, concentrating on how the simultaneous emergence of climatic, economic and political threats affects the functioning of food systems. While the study highlights the need for systemic management, it does not provide a quantitative basis or forward-looking projections. By contrast, S. Das *et al.* developed a strategic risk assessment model for grain supply chains, applying a businessoriented approach to sustainable development. Both approaches offer valuable conceptual insights but lack in-depth analysis of production volumes, consumption, price dynamics and crosscountry differences, all of which are addressed in detail in this study through a combined empirical and forecasting model.

D. Prajapati *et al.* (2022) and M. Kanan *et al.* (2023) provided important practical insights into operational improvements in the agricultural sector. D. Prajapati *et al.* proposed an approach to environmentally sustainable routing in grain e-commerce, focusing on reducing logistical costs and the ecological footprint. Despite its technical innovation, the absence of an assessment of economic or climatic changes limits the model's relevance for macro-level analysis, which was addressed in the present study. Meanwhile, M. Kanan *et al.* conducted an empirical study on statistical control systems in the food industry, emphasising the need to improve quality standards. However, their approach remained narrowly focused on production and did not consider the structural transformations of agricultural markets, which this study explored through the lens of prices, demand and forecasts up to 2028.

It is also worth noting that R. Gupta & R. Shankar (2024) focused on risks and technological solutions in the food sector. They introduced the concept of blockchain traceability as a tool to enhance transparency and trust in grain supply chains. Despite its strategic value, the study did not address macroeconomic influences, demographic shifts or climate risks, which are key elements in the present model. In turn, M. Letta *et al.* (2022) analysed market responses to weather shocks, emphasising the importance of price expectations among traders in an increasingly unstable climatic environment. While this approach partially aligns with the current findings, it lacks the systemic cross-country assessment that this study implements through structural comparison.

Attention should also be given to the research by J. Yang *et al.* (2021), which contributed to understanding the exchange and geopolitical factors shaping the grain market. The researchers conducted a comprehensive analysis of China's agricultural futures markets, focusing on the mechanisms of exchange price formation. While the findings are significant, the study remained confined to the national financial system, without integrating factors such as international trade, climate change, or the internal structure of consumption. In contrast, A. Rose *et al.* (2023) examined the impact of military conflict on global grain export flows, particularly in the context of Ukraine. This approach holds considerable political relevance; however, the study did not include an in-depth analysis of production-consumption systems or adaptive technologies, which form the foundation of the present study's scenario-based modelling. Compared with individual studies, this research encompasses a broader geographical, economic and temporal scope, offering a deeper understanding of the transformational processes within the global agricultural system. The findings not only align with selected scientific conclusions but also enhance them through an interdisciplinary, forwardlooking analysis that holds practical value for strategic planning in the agricultural sector.

In conclusion, the results of the study demonstrate the advanced development of the grain market, particularly in Ukraine and leading global producers such as China, the USA, India, Brazil and EU countries. The projected increase in grain production by 2028 indicates stable demand for this strategic resource, while the rising share of grain used for feed is reshaping domestic market structures in many countries. Notably, Ukraine's adaptation to logistical constraints and the need to modernise infrastructure are critical for maintaining and expanding its export potential.

CONCLUSIONS

In the course of the study, a comprehensive analysis was conducted of the logistical factors affecting the functioning of Ukraine's grain market during the war and the period of geopolitical instability from 2022 to 2024. Particular attention was given to changes in the export structure, the development of processing infrastructure, and issues related to domestic consumption and state support. According to the findings, total grain production in Ukraine reached 54.2 million tonnes in 2024. This figure confirmed the significant role of the grain sector in meeting both domestic and external demand, with exports accounting for over 65% of total production. Maize constituted the largest share of grain exports, representing more than 61% of the total. The geographical structure of exports showed a high concentration in a limited number of importing countries, notably China, Spain, Egypt, Turkey and Indonesia, highlighting the strategic importance of the Asian and Mediterranean markets for Ukraine. One of the key challenges that emerged during the war was the reconfiguration of logistical routes. Due to the maritime blockade, the share of rail transport rose from 27.3% in 2022 to 35.2% in 2024. This shift was a necessary response to offset the decline in maritime exports; however, rail transport faced limitations in capacity and incurred high logistical costs. The study also focused on evaluating the effectiveness of government compensation programmes for farmers, which constituted a vital element of support for Ukraine's agricultural sector. It was found that although the number of applications for compensation increased, the approval rate declined, indicating the presence of bureaucratic barriers and budgetary constraints. The total amount of compensation disbursed in 2024 was 2.7 billion UAH, which was lower than in the previous year. Overall, the study demonstrated that Ukraine's agricultural sector continued to adapt to new conditions. Nonetheless, for sustainable development amid global economic challenges and domestic difficulties, it is essential to strengthen state support, streamline compensation procedures, and develop alternative transport routes for grain exports. A key limitation of the study is its dependence on the availability of statistical data and the lack of complete information for certain regions. Future research could focus on a more in-depth analysis of climate scenarios and the impact of innovative technologies on the efficiency of grain production.

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Функціонування ринку зерна в умовах глобальних викликів: теоретико-прикладні аспекти

Анотація. Метою дослідження був аналіз структурних змін і факторів впливу на динаміку аграрних ринків для формування обґрунтованих прогнозів їх розвитку. При проведенні дослідження були використані методи економіко-статистичного аналізу, регресійного моделювання, факторного та кореляційного аналізу, а також прогнозування на основі моделей машинного навчання. У статті представлено комплексну оцінку стану ринку зерна в Україні за результатами 2024 року. Дослідження зосереджено на аналізі обсягів виробництва, структури експорту та внутрішнього споживання зернових культур, включаючи пшеницю, кукурудзу, ячмінь, жито, овес та інші. Встановлено, що валовий збір зерна в Україні у 2024 році склав 54,2 млн тонн, при цьому експортовано було 35,4 млн тонн, що становило понад 65 % від виробленого. Основними експортними культурами залишались кукурудза (21,7 млн тонн) та пшениця (11,9 млн тонн). У структурі споживання найбільшу частку займали кормові цілі

(11,7 млн тонн), продовольчі потреби (5,1 млн тонн) та технічні потреби з насінням (2,0 млн тонн). Також було проаналізовано географію експорту, зокрема концентрацію поставок у Китай, Іспанію, Єгипет, Туреччину та Індонезію, на які припадало понад 56 % експорту. Окрему увагу приділено інфраструктурним обмеженням (зниження потужностей зберігання на 3,8 %), логістичним каналам перевезень (66 % – морськими портами, 29 % – залізничним транспортом), а також динаміці цін на основні культури: середні ціни склали $ 232/т для пшениці, $ 187/т для кукурудзи та $ 198/т для ячменю. Зроблено висновок, що зростання виробництва та споживання супроводжується структурними змінами, підвищенням ролі технологій, зростанням витрат і потребою в адаптаційній політиці. Україна має потенціал зберегти 9-10 % частки світового експорту кукурудзи за умов подальшого розвитку інфраструктури та стабілізації логістики. Результати дослідження можуть бути використані для розробки аграрної політики, оптимізації експортної логістики та формування економічних стратегій у сфері зернового виробництва

Ключові слова: продовольча безпека; аграрна політика; експортний потенціал; кліматичні ризики; логістичні виклики