Research Article

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VALUE-CHAIN DIGITAL CONTROL MODEL OF CAPITAL INVESTMENT OPTIMISATION AND QUALITY ASSURANCE IN FARM-TO-FORK SYSTEMS

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Background. Logistical gaps and territorial deformations of production capacities create unprecedented challenges for the dairy industry. This requires modernising capital investment management by transitioning to strategic investment in intelligent control systems, revising financial mechanisms, and integrating environmental sustainability into the “from farm to fork” concept to ensure enterprise viability.

Purpose. The purpose is to substantiate the development of a model for capital investment management by integrating end-to-end digital technologies into the “farm-to-fork” value chain, combining physical asset management (CAPEX) with the implementation of biogas (Bio-CNG) infrastructure.

Findings. Analysis of the dynamics of gross milk production and investment activity in Ukraine in 2020–2024 revealed a deep structural transformation of the dairy market, characterised by a transition to intensive business models and the redistribution of production capacities toward the western and central regions. The strategic architecture of investment support enabled the formation of a holistic system of digital control over capital investments, ensuring the transition from spontaneous capacity renewal to strategic management of financial resources and increased enterprise competitiveness in the global dairy market. The use of AI-based predictive maintenance and digital twins optimises CAPEX and reduces OPEX by integrating renewable energy (Bio-CNG) into the logistics chain. The proposed model demonstrates how digital transparency creates premium value for products through eco-labelling and blockchain verification. The implementation of the Value-Chain Digital Control Model ensured a 75% increase in net profit, an increase in return on investment from 20% to 35% (by 15 percentage points), and a 44% reduction in the payback period (from 5 to 2.8 years).

Implication. The dairy sector demonstrates adaptive resilience, with a trend toward producing high-value-added products for export. The developed digital architecture “from farm to fork” (Blockchain and Internet of Things) provides end-to-end quality control and protection of intellectual capital. The integration of bio-CNG infrastructure is a critical driver of energy independence and reduced logistics costs. Digital modernisation, combined with social and environmental responsibility, is identified as a priority mechanism for ensuring the competitiveness of Ukrainian dairy enterprises in the EU markets.

Keywords: Biogas, Blockchain, Dairy Industry, Investment Management, Supply Chain Management.

1. Introduction.

Against the backdrop of wartime and post-war conditions in Ukraine, the dairy industry faces unprecedented challenges, including political turbulence, disruptions to logistics networks, and the fragmentation of production capacities across territories. Modernisation of the mechanism for managing capital investments at dairy processing enterprises is impossible without the widespread adoption of digitalisation tools that enable moving from spontaneous renewal of fixed assets to strategic investment in intelligent control systems. The organisational reform of agribusiness is an important basis for such transformations, as it lays the institutional foundation for adapting economic structures to changing market conditions.

Soteriades et al. (2018) claim that implementing innovative methods for feed and manure management significantly reduces the ecological footprint of dairy farms without compromising economic efficiency.

The effectiveness of investment processes in modern conditions directly depends on the transparency of the information environment; in particular, high-quality financial reporting is a critical factor for the objective assessment of enterprise performance and capital attraction (Pravdiuk et al., 2021).

The industry's digital transformation requires a reassessment of traditional mechanisms for resource and financial management. In particular, the use of supply chain financing tools and modern inventory management systems is critical for optimising capital investments, especially for products with a limited shelf life (Marchi et al., 2024).

It is the synergy between environmental sustainability and digital financial technologies that underpins an effective architecture for managing capital investments in dairy processing enterprises within the Farm-to-Fork Strategy framework. At the same time, the industry's strategic development should focus on sustainable marketing, enabling Ukrainian agricultural enterprises not only to adapt to internal challenges but also to compete successfully in global food markets (Belkin et al., 2025).

Despite significant theoretical developments, the practical implementation of end-to-end digital control systems in Ukrainian realities remains insufficiently explored. The identified need to develop a comprehensive model of digital supply chain management shapes further research on the practical implementation of agri-food chains and addresses the lack of an applied model that simultaneously optimises capital investments (CAPEX) under limited resources and ensures end-to-end quality control of food products.

The purpose of the study is to substantiate the theoretical and methodological principles and develop applied tools for forming a model of capital investment management of dairy processing enterprises, based on the integration of end-to-end digital technologies (blockchain, IoT, AI) into the farm-to-fork value chain to ensure investment sustainability, environmental safety, and energy independence of the industry under martial law. To achieve the research aim, the following research questions (RQs) were identified:

RQ1. To assess the dynamics of gross milk production, investment activity, and foreign trade balance of Ukraine for 2020–2024, taking into account the impact of military operations.

RQ2. To investigate the territorial configuration of the dairy industry and identify the main centres of added value formation and investment leadership.

RQ3. To develop an author's model of an end-to-end digital control system that integrates blockchain technologies, the industrial IoT, and artificial intelligence to ensure the quality and protection of capital investments.

RQ4. To substantiate the mechanism of combining physical asset management (CAPEX) with the implementation of biogas infrastructure and adaptive management methods to increase the sustainability of enterprises.

Therefore, the development and implementation of an end-to-end digital control system is a strategic tool for transforming Ukrainian dairy processing enterprises into modern and highly efficient agribusiness facilities.

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2. Literature Review.

2.1. Farm-to-Fork Concept.

The current state of the global and domestic food industry is characterised by deep transformation, driven by the need to balance economic efficiency, environmental sustainability, and consumer demands. The key concept uniting these aspects is the "farm-to-fork" model, which aims to optimise supply chains and increase the transparency of production processes.

The genesis of the "farm-to-fork" concept is closely related to the transformation of consumer values and the search for alternatives to globalised food systems. A fundamental contribution to understanding the importance of local connections was made by Waters (2007) demonstrated the dependence of final product quality and agricultural sector sustainability on ethical attitudes towards the land and direct support for small producers. This approach transformed the gastronomic niche into a systemic movement for transparency in the origin of food products.

This initiative has evolved into a global sustainability initiative. Pollan (2006) argues that the gap between the "farm and fork" in the modern industrial system has resulted in a loss of control over energy costs and nutritional quality. Reducing the supply chain is considered the only way to restore food sovereignty and minimise climate impacts. This concept has become an official strategy for developing agro-industrial complexes in developed countries. According to the European Commission (2020), the transition to a sustainable food system requires not only changes in consumption culture but also a digital transformation of production processes. This creates the prerequisites for a new architecture of capital investment management, where information about each stage of a product's movement, from primary raw materials to final sale.

Kelly et al. (2025) stated that understanding the aspects of milk transformation at each stage of the chain, from lactation biology to complex processing technologies, is critical to ensuring product integrity and compliance with modern quality standards.

It should also be noted that food safety remains a global problem, as hazardous substances can occur throughout the food supply chain, from farm to fork (Tian et al., 2025).

In contrast to the residual approach, Serpeninova et al. (2024) identified an approach that considers social responsibility as compensation after profit is made. An integrated approach involves incorporating economic, social, and environmental factors (particularly quality control along the "farm-to-fork" chain) directly into decision-making. This creates conditions for ensuring economic development by considering the environmental and social consequences of an enterprise's activities.

Furthermore, Koval et al. (2025) showed that dairy enterprises face a wide range of challenges, including political and economic turbulence, disruptions in logistics networks, and changes in consumer sentiment.

The modern "farm-to-fork" paradigm requires a comprehensive quality assurance approach that begins at the genetic potential and feeding stages of the animals. Mukherjee et al. (2025) argue that the transition from conventional breeding systems to sustainable production in the genomic era is the foundation of global food security, as it enables the programming of product quality characteristics at the breeding level.

Precision nutritional approaches accompany this process. In particular, Kazemi and Valizadeh (2025) as well as Mukherjee et al. (2025) emphasised that the implementation of innovative feeding strategies is a key lever for increasing the biological value and safety of animal-based food products that meet the growing consumer demand for functional foods.

An important aspect of the dairy market evolution is the differentiation of products based on health benefits. Manuelian et al. (2025) found that consumer acceptance of innovative products, such as type A2 milk, creates new niches and potential markets, requiring producers to be transparent about the production and consumption practices. This confirms that modern quality is not only about meeting standards but also about the ability to meet specific consumer needs within the farm-to-fork chain.

Digitalisation unites these processes technologically. According to a systematic review (Serrano-Torres et al., 2025), transforming dairy supply chains through AI enables end-to-end real-time quality control. This creates a solid foundation for a capital investment management architecture that leverages AI to minimise risks, optimise logistics, and guarantee product authenticity, critical to ensuring the resilience of dairy processing enterprises in crisis conditions.

The "farm-to-fork" concept and the corresponding investment architecture are particularly relevant to overcoming the destructive consequences of military operations on Ukraine's agricultural sector.

Nitsenko et al. (2025) argue that the current state of domestic agribusiness requires the immediate revitalisation of logistics and handling operations activities and the strategic relocation of logistics processes. In the context of territorial deformations and the blocking of traditional routes, effective risk management and flexible restructuring of logistics chains are critical for maintaining the viability of the industry's export and domestic potential. This directly correlates with the need to develop digital models of capital investment management that enable dairy processing enterprises to quickly adapt their value chains to the changed conditions resulting from the dislocation of production facilities and new logistical challenges.

The identified shortcomings of the developed sources indicate the fragmentation of investment models that do not offer clear capital management algorithms in conditions of limited resources and high risks of asset destruction. Thus, there is an objective need to develop an integrated investment management model that combines environmental "farm-to-fork" standards with flexible anti-crisis marketing methods and digital control.

2.2. Digital Management of Capital Investments.

In the context of digitalisation, the technological architecture for managing dairy investments is shifting from equipment renewal to the creation of intelligent systems.

The synergy of artificial intelligence, IoT, and Blockchain provides end-to-end quality control from "farm-to-fork", optimising resources and strengthening the enterprise's intellectual capital. Military challenges require implementing flexible Agile methods to rapidly relocate logistics and adapt investments to the risks of asset destruction. Thus, digital architecture becomes the foundation for energy independence and the industry's survival in turbulent conditions.

Czeglédi (2025) eliminated the gap between the cultivation and consumption of agricultural products. The corresponding model promotes a direct connection between producers and end consumers. Although a "farm-to-fork" model is the shortest, this streamlined approach minimises logistical and administrative complexities, reducing the distance and time between harvest and consumption to a minimum.

Kelly et al. (2025) argue that, despite the very long history of dairy products and their high level of consumption in the world today, the future of the dairy industry is now perhaps under greater threat than at any time in history, with the emergence of concerns about the health, ethical and environmental impacts of dairy production, as well as the rise of veganism and the associated desire to find alternatives to dairy products.

According to Subbotina-Dubinski and Carbon (2025), the main thematic clusters related to changes in the food industry in general (sustainable food practices) and dairy in particular (empirical dimensions of food).

Yin (2025) and Mosiuk et al. (2025) argued that cognitive and emotional reactions of customers mediate the influence of restaurant incentives, especially environmental practices, on pro-environmental behaviour and behavioural intentions of consumers during dining, thereby influencing the effective development of responsible strategies in environmentally conscious food establishments. This shift towards responsible consumption and reputation-based value creation has a direct impact on capital investment management in the agri-food sector, particularly in dairy processing.

Lohosha et al. (2024) argue that efforts should be made in Ukraine to develop a separate, original regulatory concept based on a contractual approach (as an internal mechanism for coordinating the actions of economic agents in the market). State regulation (as an external instrument for shaping regulatory rules governing the behaviour of market participants/relationships) to achieve an acceptable market state.

Chikov and Titov (2025) show that modernising the mechanism for capital investment management at dairy processing enterprises is impossible without widespread digitalisation. It allows moving from the spontaneous renewal of fixed assets to strategic investment in intelligent control systems, which becomes the foundation for increasing the industry's competitiveness.

It is worth noting that, according to Popovych et al. (2023), the economic efficiency of digitalisation in the dairy sector is manifested in increased labour productivity and reduced costs through resource optimisation. Stavska et al. (2022) indicated that agile development helps product groups deliver software that meets customers' growing needs.

Simultaneously, the successful implementation of an end-to-end digital control system in dairy processing enterprises depends not only on technical equipment but also on the intellectual basis of the organisation. Pidvalna et al. (2022) argue that developing an innovative strategy should be based on building intellectual capital, which is imperative for ensuring the sustainability of enterprises in the context of digitalisation.

Ensuring the sustainable development of the agri-food sector, particularly the dairy industry, is only possible using an integrated approach. While Serpeninova et al. (2024) and Koval et al. (2025) emphasise the importance of corporate social responsibility and sustainable management, Chikov and Titov (2025), Popovych et al. (2023), and Stavska et al. (2022) indicate that the technical foundation of sustainability is digitalisation, the implementation of IoT tools, and agile management.

However, despite significant research on the "farm-to-fork" concept and the importance of intellectual capital (Pidvalna et al., 2022), the issue of the practical implementation of end-to-end digital control systems in the context of the war- and post-war economy of Ukraine remains insufficiently covered. In particular, the mechanism of combining contractual market regulation (Lohosha et al., 2024) with technological innovations to address logistical gaps and personnel shortages (Mosiiuk, 2026) requires further study.

Thus, the need to develop a comprehensive model of digital supply chain management that integrates intellectual property, social responsibility, and high food safety standards has been identified, which will determine the direction of this research.

3. Methodology.

The research methodology is based on a complex combination of general scientific and specialised methods that enable a deep analysis of the investment architecture of the dairy industry under martial law and in the context of digital transformation.

The research process begins with a retrospective analysis of the dynamics of milk production and the cow population for 2020–2024, which enables identification of critical points of decline in raw material volumes and deformation of the industry's territorial structure. At the next stage, the method of statistical and economic screening was applied to assess capital investments and export-import operations, thereby enabling the determination of the level of financial stability of dairy processing enterprises.

An important place in the work is occupied by the method of economic and mathematical modelling, which was used to design a digital control system for the "farm-to-fork" strategy, integrating blockchain, artificial intelligence, and IoT tools to minimise operating costs. In addition, the study substantiates the implementation of energy-efficient infrastructure based on Bio-CNG, as demonstrated by return on investment (ROI) and capital expenditure optimisation (CAPEX) indicators.

Verification of the results is carried out by comparing theoretical models with actual data from the State Statistics Service of Ukraine (2025) and customs reporting, which confirms the practical value of the proposed solutions for increasing the investment attractiveness of the agricultural sector. The use of a systemic approach enables the development of a holistic vision of the dairy business as a vertically integrated structure capable of adapting to global challenges and meeting European quality standards. The model is based on the calculation of the effectiveness of cost optimisation:

$$ROI = \frac{NetProfit}{InvestmentCost} * 100\% \quad (1)$$

To assess the impact of digital control on operating expenditures (OPEX), the functional dependence is used:

$$\Delta OPEX = (C_{log} + C_{maint}) - (E_{bio} + E_{ai}) \quad (2)$$

where,

C_{log} – costs on traditional logistics;

C_{maint} – costs on reactive equipment maintenance;

E_{bio} – savings from the use of BioCNG;

E_{ai} – savings from the implementation of AI-predictive maintenance.

The methodology for developing the model of an end-to-end digital control system involves integrating technological tools into a single architecture to optimise capital investments across the value chain. The methodology is based on an algorithm for identifying key "farm-to-fork" links and the selection of appropriate digital technologies, such as blockchain to ensure the safety of raw materials, industrial IoT for predictive maintenance of equipment, and artificial intelligence for modelling energy-efficient solutions.

The model is developed by combining CAPEX with intellectual property protection and the implementation of adaptive management methods (Agile management). The final stage of building the model involves systematising economic components, where the use of digital twins and quality verification systems maximises net profit, ensures energy independence through Bio-CNG infrastructure, and creates premium product value in global markets.

The proposed investment architecture for the dairy industry is based on the concepts of vertical integration and the digitalisation of the full value-creation cycle, in line with the "Farm-to-Fork" Strategy (Fig. 1).

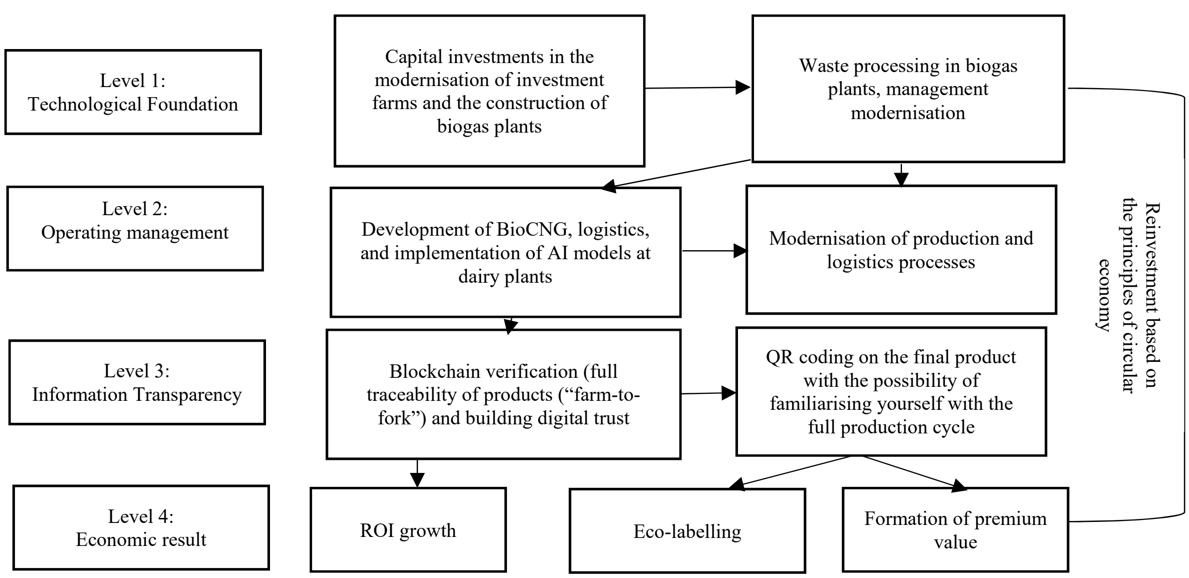

Fig. 1. Strategic Framework for Sustainable Dairy Investment under Green and Digital Transition.

The model is based on a systematic combination of a technological foundation, including investments in IIoT sensors and biogas infrastructure for the production of Bio-CNG fuel, with a digital level of operational management based on artificial intelligence. The industry transformation process is implemented through a blockchain-based verification mechanism at each stage of product movement, providing absolute transparency and traceability for the end consumer.

Economic efficiency is achieved through radical optimisation of operating costs and the creation of premium value for environmentally labelled products, which directly correlates with the growth of investment profitability indicators and the enterprise's overall investment sustainability in the face of global challenges. The model's closed cycle involves the constant reinvestment of profits into the development of innovative infrastructure, creating a sustainable circular ecosystem for the dairy business. The analysis does not cover temporarily occupied territories or combat zones.

The BioCNG infrastructure model is considered a tool for optimising logistics, specifically for large and medium-sized milk plants with an intensive business model.

4. Results.

4.1. Analysis of the State of the Dairy Processing Industry in Ukraine.

The analysis of milk production volumes and industry activities indicates a deep structural transformation of Ukraine's dairy market, characterised by a transition to intensive business models amid a gradual reduction in the total number of cows from 2.54 million in 2013 to a projected 1.15 million in 2025.

Despite the overall decrease in the volume of milk supplied for processing, there is a qualitative increase in the role of the industrial sector, where the volume of raw material supplies from agricultural enterprises increased to 2.88 million tons in 2024, which confirms the dominance of professional farms in ensuring food stability (Fig. 2).

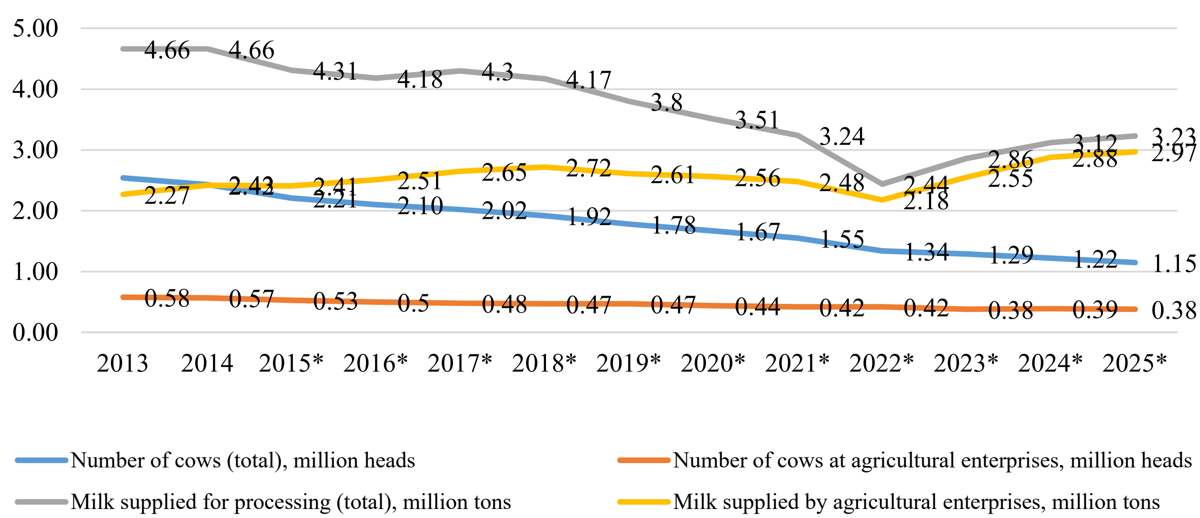

Fig. 2. Dynamics of Cow Population and Milk Supply for Processing in Ukraine.

** - data are updated without temporarily occupied territories.*

Source: based on data Association of Milk Producers (2025).

Despite martial law and the loss of part of the production capacity, in 2024, the agricultural sector of Ukraine recorded a gross milk production volume of 7,246.4 thousand tons, which indicates a deep transformation of the industry and a change in its territorial configuration (Fig. 3). The current state of dairy cattle breeding is characterised by pronounced regional concentration, where the leading positions are occupied by Poltava, Vinnytsia, and Khmelnytsia regions, which together provide a significant share of national raw material production due to the preservation of livestock and high productivity of the industrial herd.

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At the same time, indicators are severely depressed in the eastern and southern regions, particularly in Luhansk, Donetsk, and Kherson, where hostilities and the destruction of infrastructure have led to a critical reduction in production capacity (Nitsenko et al., 2025). The general trend in the industry's development indicates the gradual replacement of extensive household production by a more technologically advanced industrial sector, which demonstrates resilience to external challenges and becomes a key guarantor of the state's food security.

Thus, the geographical distribution of milk production in 2024 reflects the adaptation of the agro-industrial complex to new realities, with the central and western regions serving as the main sources of raw materials for the dairy industry.

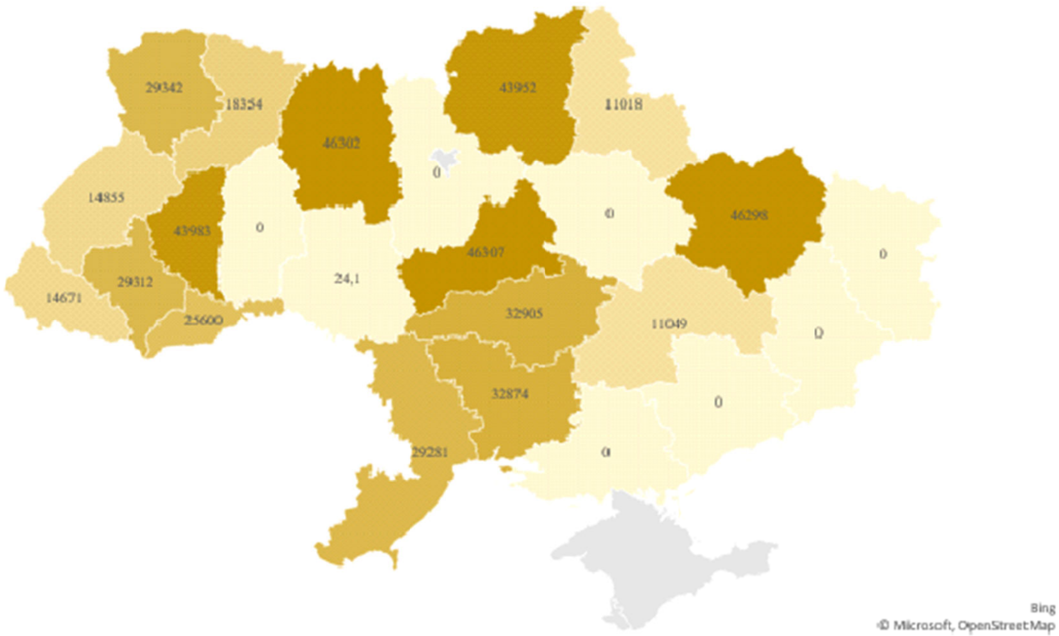

Fig. 3. Dairy Production by Region, January 1, 2025 (Excluding Temporarily Occupied Territories).

Source: based on Association of Milk Producers (2025); State Statistics Service of Ukraine (2025) using the Microsoft Bing Search API platform.

At the same time, the analysis of investment activity in Ukraine's dairy processing sector as of January 1, 2025 demonstrates the industry's adaptive resilience to exogenous challenges and its gradual technological restructuring. The main capital expenditures, totalling USD 164.8 million, are concentrated in regions with high concentrations of industrial livestock farming (Fig. 4).

This confirms the strategic leadership of Vinnytsia, Kyiv, and Poltava regions as the main centres of added value. The territorial structure of investments reflects the priority of modernising existing capacities through the implementation of "farm-to-fork" energy-efficient solutions and digital quality control tools, which are critically important for increasing export potential in the context of European integration.

At the same time, the dynamics of investments in western regions, particularly Khmelnytskyi and Lviv, indicate active processes of decentralising processing capacities and their approximation to new consumer markets.

At the beginning of 2025, the investment environment is characterised by a transition from point recovery to systemic technological renewal aimed at maximising ROI (Return on Investment) and ensuring the sustainable development of the dairy sub-sector of the agro-industrial complex.

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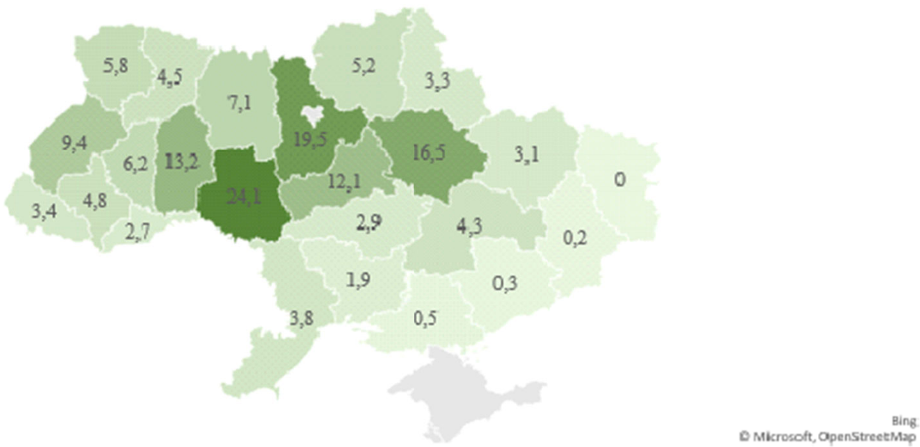

Fig. 4. Volumes of Investments in Dairy Processing Enterprises, January 1, 2025, million USD (Excluding Temporarily Occupied Territories).

Source: based on Association of Milk Producers (2025) using the Microsoft Bing Search API platform.

Analysis of the balance of milk production and consumption in Ukraine in 2020–2024 indicates a significant reduction in gross production by 2,017.2 thousand tons, which is due to the destruction of enterprises and the loss of livestock due to military actions (Fig. 5). The total consumption of dairy products in the country decreased by 1,450.66 thousand tons, which is directly correlated with the decrease in the population due to migration. Despite the general negative trends, the volume of raw materials supplied for industrial processing increased by 666.7 thousand tons, indicating a gradual technological transformation and the displacement of extensive household production by the industrial sector. Simultaneously, positive dynamics of milk consumption per capita were recorded. It increased by 8.4 kg/person, although in 2024, the actual figure of 210.3 kg remained significantly below the established rational nutrition standards. Analysis of the dynamics of foreign dairy trade in 2020–2024 demonstrates a significant transformation in the structure of the Ukrainian market, characterised by a shift from import dependence in certain categories to greater export potential (Table 2).

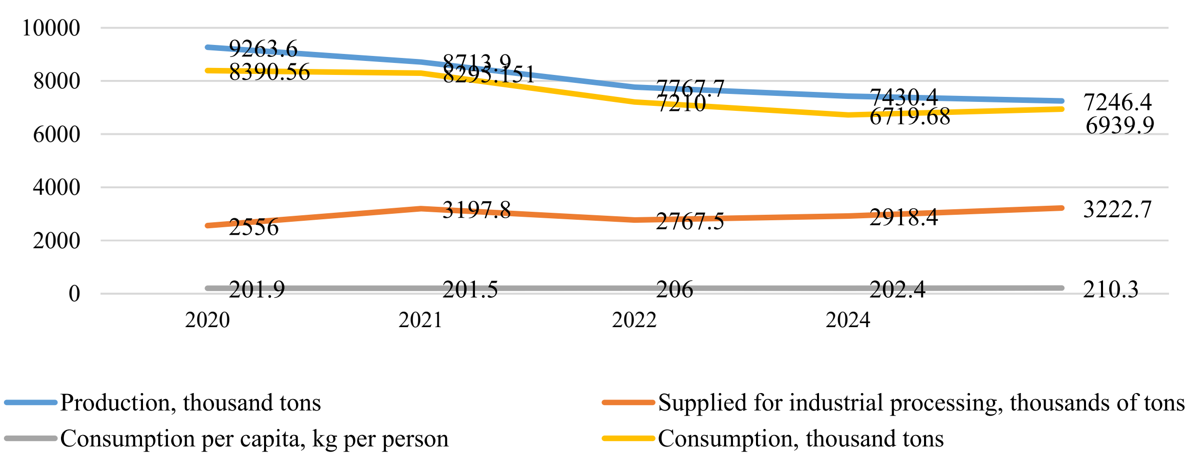

Fig. 5. Balance of Milk Production and Consumption in Ukraine, 2020-2024.

Note: Data exclude the temporarily occupied territories of the Autonomous Republic of Crimea, the city of Sevastopol, and parts of the Donetsk and Luhansk regions. Data exclude territories temporarily occupied, as well as areas where active hostilities have occurred or are ongoing.

Source: based on Association of Milk Producers (2025).

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Table 2. Volume of Imports and Exports of Dairy Products (thousands USD), 2020–2024.

Product (UKTZED Code)	Import Cost	Import Share	Import Net weight, t	Export Cost	Export Share	Export Net weight, t
2020						
Milk and cream, not condensed	11,624	0.02%	12,969	12,006	0.02%	18,642
Milk and cream, condensed	14,005	0.03%	6,144	55,529	0.11%	27,417
Buttermilk, fermented or soured milk, and cream	14,029	0.03%	9,921	8,974	0.02%	5,694
Whey	6,920	0.01%	5,062	22,304	0.05%	26,904
Butter	40,580	0.07%	10,012	48,733	0.10%	11,229
Cheese	210,487	0.39%	46,767	24,414	0.05%	6,358
2021						
Milk and cream, not condensed	13,377	0.02%	14,369	10,372	0.02%	14,922
Milk and cream, condensed	21,204	0.03%	7,799	57,366	0.08%	22,426
Buttermilk, fermented or soured milk, and cream	20,008	0.03%	14,005	8,649	0.01%	5,504
Whey	12,335	0.02%	9,628	22,821	0.03%	22,218
Butter	45,529	0.06%	9,148	52,308	0.08%	10,858
Cheese	260,329	0.36%	55,193	26,692	0.04%	6,924
2022						
Milk and cream, not condensed	8,594	0.01%	9,386	16,387	0.04%	29,350
Milk and cream, condensed	4,027	0.01%	1,214	89,983	0.20%	26,696
Buttermilk, fermented or soured milk, and cream	14,938	0.03%	9,456	4,668	0.01%	3,055
Whey	6,904	0.01%	4,917	15,765	0.04%	15,269
Butter	7,910	0.01%	1,128	81,742	0.19%	14,104
Cheese	182,159	0.31%	33,818	42,278	0.10%	8,989
2023						
Milk and cream, not condensed	6,069	0.01%	5,126	16,572	0.05%	28,315
Milk and cream, condensed	4,738	0.01%	1,263	68,670	0.19%	27,676
Buttermilk, fermented or soured milk, and cream	17,376	0.03%	8,670	4,172	0.01%	3,353
Whey	12,474	0.02%	6,887	10,854	0.03%	16,181
Butter	16,633	0.03%	2,657	41,770	0.12%	7,790
Cheese	200,774	0.32%	33,685	39,962	0.11%	8,879
2024						
Milk and cream, not condensed	4,048	0.01%	2,021	17,620	0.04%	26,601
Milk and cream, condensed	5,321	0.01%	1,520	74,284	0.18%	29,487
Buttermilk, fermented or soured milk, and cream	16,820	0.02%	8,189	5,917	0.01%	4,375
Whey	10,813	0.02%	6,088	13,377	0.03%	18,685
Butter	18,577	0.03%	2,576	48,897	0.12%	7,178
Cheese	227,088	0.32%	38,284	54,208	0.13%	12,428

Source: based on State Customs Service of Ukraine (2025).

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Cheese remains the most significant import item throughout the entire period, and its value reaches USD 227.1 million in 2024, an increase of 8,483 tons from 2020. Simultaneously, the export sector experienced rapid growth in condensed milk and butter, with sales peaking in 2022, when butter exports almost doubled from the previous year to USD 81.74 million. Despite the general trend of increasing exports of whole milk and cream by 7,959 tons, deliveries of buttermilk and whey abroad showed a negative deviation, indicating a reorientation of domestic processing.

As of 2024, domestic producers significantly strengthened their positions in foreign cheese markets, increasing exports by 6.1 thousand tons, compared to the base period. Together with the dominance of condensed milk in the export structure, this underscores the industry's strategic development of high-value products. The reduction in the imports of butter and non-condensed dairy products in 2022–2024, compared to 2021, indicates successful import substitution and the dairy sector's adaptation to crisis operating conditions.

The identified negative deviation in the export of certain categories, along with the preservation of a high share of cheese imports, underscores the need for new competitiveness tools that focus on the digital management of the value chain.

The analysis of the foreign trade balance and regional investment structure indicates the presence of an institutional trap. Despite increased industrial sector efficiency, the industry remains vulnerable to fluctuations in energy carrier prices and the strict requirements of European safety standards. This determines the objective need to transition from fragmented automation to a comprehensive digital architecture that integrates physical asset management (CAPEX) with the protection of the enterprise's intellectual capital.

4.2. Digital Transformation of the Farm-to-Fork Value Chain for European Market Integration.

It is worth noting that the transformation of the Ukrainian dairy sector under war conditions involves not only relocating production facilities but also deep digital modernisation, which is key to preserving capital and entering premium European markets. Ensuring the above-mentioned sustainability of export potential and CAPEX efficiency requires a transition to fundamentally new technological foundations, which are systematised in Table 3.

Table 3. Digital Transformation and Investments Optimisation in the Farm-to-Fork Value Chain.

Strategic Task	Supply Chain Stage	Key Digital Technologies	Impact on CAPEX, ROI, and Quality Assurance
Blockchain-based traceability for digital raw material management, ensuring product origin, quality, and safety.	Farm → Processing	Blockchain, IoT Sensors	Improved traceability, enhanced quality assurance, reduced food safety risks, and lower production losses.
Predictive maintenance to safeguard investments in critical processing equipment.	Processing	IIoT, AI-based Predictive Maintenance	Cost and downtime reduction, improved reliability, and CAPEX preservation.
Strategic investment in biogas production and Bio-CNG infrastructure to reduce logistics-related operating costs and strengthen energy resilience.	Recycling / Biogas Production	Digital Twins, AI-Based Modelling	Improved justification of CAPEX allocated to biogas facilities through long-term OPEX savings, waste valorisation, and enhanced energy independence.
End-to-end monitoring of green logistics through cold-chain control and optimisation of Bio-CNG-powered transport routes.	Logistics	IoT Sensors, GPS/Telematics, AI Optimisation	Improved product quality and safety during transportation. Efficient utilisation of logistics assets and reduced transportation costs.
Maximising return on investment through digital transparency, sustainable logistics, and consumer-oriented value creation.	Consumer / Market	Blockchain, Digital Marketing Integration	Faster ROI driven by consumer trust, brand loyalty, and willingness to pay a premium for certified quality and sustainability.

As a result of the research, we conducted a comprehensive analysis of the implementation of innovative technologies at each stage of the agri-food cycle.

It reveals the mechanisms for integrating blockchain, the Industrial Internet of Things (IIoT), and artificial intelligence to ensure end-to-end transparency of raw material flows, predictive maintenance of expensive equipment, and justification of capital investments in renewable energy, in particular, Bio-CNG infrastructure.

The production of biogas from dairy processing waste is particularly relevant given rising energy prices. In general, the application of this chain demonstrates the transition to a sustainable, high-tech agribusiness model, where environmental responsibility and digital verification become key drivers of higher margins and premium product value in the market. The comprehensive architecture of the digital management model for the farm-to-fork chain, presented in Table 4, reveals a multifaceted approach to transforming dairy processing enterprises through the synergy of technological transparency, capital management, and strengthening the organisation's intellectual base. This structure demonstrates how integrating blockchain, industrial IoT, and AI modelling tools not only enables end-to-end control from farm to consumer but also provides a reliable foundation for enterprise sustainability amid global digital transformations. Particular attention in the architectonics is paid to the combination of social and environmental responsibility with adaptive management methods, which, through the implementation of Agile management and "green" infrastructure, helps overcome logistical gaps and increase business margins by creating a premium value for the end consumer.

Table 4. Digital Management Architecture for the Farm-to-Fork Value Chain in Dairy Processing Enterprises.

Component of the Model	Key Tools and Technologies	Object of Integration and Influence	Economic and Social Impact
Technological Transparency and Security	Blockchain, IoT sensors, AI modelling	End-to-end control from farm to end consumer	Minimising food safety risks and ensuring product quality
Capital and Investment Management	Predictive maintenance (IIoT), digital twins	Protection of expensive equipment and assets (CAPEX)	Reducing unforeseen costs, maximising ROI, and achieving energy independence
Intellectual Capital Development	Protection of intellectual property, development of intellectual capital	Innovative development strategy and commercialisation of ideas	Formation of economic sustainability of the enterprise in the context of digital transformations
Socio-Environmental Responsibility	Sustainable food practices, Bio-CNG infrastructure, ESG reporting	Corporate social responsibility and environmental verification	Increasing marginality through the formation of premium value for the conscious consumer
Adaptive Management	Agile management (Management 3.0), anti-crisis marketing	Flexibility of production and logistics chains in wartime	Overcoming logistical gaps and personnel shortages

The systematisation of economic components of the model, presented in Table 5, reveals a specific mechanism for converting digital tools into effective financial indicators at each stage of the enterprise's capital reproduction cycle.

It displays the strategic relationship between the use of digital twins to justify investments (CAPEX) in modernisation and energy independence, and the final optimisation of the capital investment structure (Soteriades et al., 2018).

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At the production and logistics stages, the use of intelligent monitoring systems and blockchain provides effective protection of fixed assets and a significant reduction in operating expenses (OPEX), which ultimately allows for maximising net profit and ROI through the use of digital quality verification as a key factor in the formation of a premium price in the market. Thus, the developed model confirms that implementing an end-to-end digital verification system and complying with social and environmental responsibility standards are key tools for ensuring the sustainability of the agri-food sector.

This establishes the prerequisites for increasing the marginality of domestic products and their successful integration into the European economic space, based on transparency, quality, and high technological competitiveness.

The justification of the proposed model is based on the integration of digital management systems with bioenergy infrastructure, which allows maximising the efficiency of capital investments, which in 2025 were recorded at the level of USD 164.8 million for the entire food industry and USD 24.1 million directly for the Vinnytsia region using the example of an advanced dairy processing enterprise, Lityn Dairy Plant LLC (Litynskyi Molochnyi Zavod LLC).

The implementation of digital control using the Value-Chain Digital Control algorithm transforms the traditional approach to CAPEX management, reorienting resources toward the creation of intelligent monitoring systems and biomethane infrastructure, thereby increasing net profit from a conventional USD 400 to 700 thousand per year for an average facility in the industry. The main economic effect is achieved through a radical reduction in operating costs due to the complete replacement of fossil fuels with its own Bio-CNG, which frees up about USD150 thousand annually, as well as through the use of artificial intelligence for predictive maintenance of equipment, which saves additional USD 50 thousand per year on service costs.

Table 5. Economic Components and Financial Effects of the Digital Farm-to-Fork Management Model

Stage of the Capital Reproduction Cycle	Economic Tools and Technologies	Functional Role in the Model	Expected Financial Outcome
CAPEX Formation (Investment Stage)	AI modelling, Digital twins	Bio-CNG and modernisation cost justification	Optimisation of the structure of CAPEX
Production Stage (Operational Efficiency)	IoT, Predictive maintenance	Protection of fixed assets from premature wear and emergency shutdowns	Minimisation of unpredictable CAPEX, productivity growth
Logistics Stage (Distribution and Sales)	IoT monitoring, Blockchain	Ensuring the quality of raw materials and finished products in real time	Reducing OPEX for fuel and losses from product defects
Market Realisation (Value Creation)	Digital Quality Verification, Blockchain-Based Traceability	Certified quality and sustainability support premium positioning	Increased ROI, higher profit margins, and growth in net profit

The additional value in this model is generated through the blockchain quality verification mechanism, which enables capitalising on the trust of European consumers and receiving a premium of USD100 thousand per year, which is critically important within the framework of implementing the Farm-To-Fork Strategy. The application of the developed mathematical model for calculating ROI shows an increase in return on capital from 20% to 35%, which directly correlates with a reduction in the payback period of investment projects from 5 to 2.8 years (Table 6). Thus, the synergistic effect of digitalisation and bioenergy autonomy ensures not only the enterprise's energy independence but also creates a sustainable mechanism for optimising OPEX, turning technological costs into a source of strategic competitive advantage in global markets.

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Table 6. Economic Efficiency of Implementing the Value-Chain Digital Control Model at Lityn Dairy Plant LLC.

Indicator Category	Calculation Parameter	Traditional Model (Million USD)	Digital Model (Million USD)	Economic Effect
Investment Expenditures	CAPEX	2.0	2.0	Reallocation of investments toward Bio-CNG infrastructure, blockchain systems and IIoT technologies without increasing total capital expenditures.
Operating Costs	Logistics and Maintenance Costs	0.50/year	0.30/year	40% reduction in operating costs through optimised logistics, biomethane utilisation and predictive maintenance.
Revenue Enhancement	Premium Price Effect	–	0.10/year	Additional revenue generated through blockchain-based quality verification and product traceability.
Financial Performance	Net Profit	0.40/year	0.70/year	Increase in net profit by 75% (+0.30 million USD annually).
Capital Efficiency	ROI (%)	20%	35%	Improvement in return on investment by 15 percentage points.
Investment Recovery	Payback Period (PBP)	5.0 years	2.8 years	Reduction in payback period by 44%.

5. Discussion.

The sustainability of the Ukrainian dairy sector under martial law depends directly on how quickly processing enterprises adapt to new technological advancements. Comparing the territorial deformation of the industry with the pre-war period, the identified regional concentration of production in Vinnytsia, Poltava, and Khmelnytskyi regions is a strategically justified response of agribusiness to exogenous risks. This study focuses on a qualitative change in the investment structure, prioritising not simply the expansion of capacities but ensuring their deep digital modernisation.

In the context of the theoretical substantiation of the “farm-to-fork” model, which builds on Czeglédi’s (2025) ideas on the strategic importance of bioenergy in the agro-industrial complex, supplementing them with modern digital tools for managing capital expenditures is essential. Unlike Kelly et al. (2025) and Subbotina-Dubinski and Carbon (2025), who place significant emphasis on general financial support for innovative development, the model we developed focuses on technological quality verification as a direct tool for maximising the ROI indicator.

However, it can offer an applied mechanism to overcome the “institutional trap” through the synergy of blockchain, the IIoT, and artificial intelligence. Compared to existing analogues, the main advantage of the author’s model is the convergence of CAPEX and the environmental component, which allows for considering biogas infrastructure (Bio-CNG) not as a separate environmental project, but as a tool for radically reducing logistics operating expenses (OPEX). Unlike standard automation systems, the proposed architecture uses blockchain not only to track commodity flows but also to serve as a financial guarantor of investment protection for a batch of raw materials, thereby minimising the risk of product rejection at the processing stage.

An important feature of the model is the implementation of predictive asset protection systems based on AI modelling and digital twins, which enable transforming maintenance of expensive equipment from reactive to preventive, a critical need for Ukraine given its limited access to imported components. In addition, unlike rigid hierarchical management models, our development is based on agile management principles, ensuring high adaptability of logistics chains to military risks and personnel shortages.

The proposed digital architecture goes beyond classical automation, forming a holistic cost management ecosystem in which technological transparency is the main driver of domestic manufacturers' entry into premium European markets.

6. Conclusions.

Despite a full-scale invasion, the agricultural sector displays adaptive resilience. In 2024, the total milk production was 7,246.4 thousand tons. Analysis of the 2020–2024 balance revealed a significant reduction in consumption due to migration; however, the industrial processing volume increased by 666.7 thousand tons. In foreign trade, there has been a transition from import dependence to increased exports of high-value products, particularly butter and condensed milk, indicating the industry's adaptation to crisis conditions.

A pronounced regional concentration of dairy cattle breeding was identified, with Poltava, Vinnytsia, and Khmelnytsia taking leading positions. These regions emerged as the main centres for attracting capital investment (total investment in the sector reached USD 164.8 million). The territorial structure reflects the priority given to capacity modernisation in the central and western regions, which have become the main bases for raw material production, while the southern and eastern regions are in a state of depression owing to the destruction of infrastructure. A comprehensive architecture for the "farm-to-fork" model was developed based on the synergy of blockchain, IIoT, and artificial intelligence.

The model provides end-to-end transparency: blockchain guarantees the security and verification of raw material origin, IoT sensors enable real-time monitoring, and AI modelling facilitates the implementation of forecasting methods. These processes transform operational activities into a managed investment process, in which each technological link is designed to minimise risks and protect the intellectual capital of dairy processing enterprises.

The combination of physical asset management (CAPEX) with the implementation of Bio-CNG infrastructure is a key driver of the sustainability of dairy processing enterprises, especially amid rising energy prices. Using digital twins to justify investments in biogas production enables a radical reduction in operational logistics costs and ensures energy independence.

Therefore, the digital modernisation of Ukraine's dairy sector, integrated with principles of social and environmental responsibility, is the only effective mechanism for preserving capital and ensuring the competitiveness of domestic enterprises in the EU markets.

Conflict of Interest Statement.

The authors declare that there is no conflict of interest.

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