МЕНЕДЖМЕНТ

UDC 005.218:330.341.424]:664
DOI: https://doi.org/10.32782/2708-0366/2024.22.19

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CREATING A SUSTAINABLE SUPPLY CHAIN IN THE FOOD INDUSTRY USING INDUSTRY 4.0 TECHNOLOGIES

СТВОРЕННЯ СТІЙКОГО ЛАНЦЮГА ПОСТАЧАННЯ У ХАРЧОВІЙ ГАЛУЗІ ЗА ДОПОМОГОЮ ТЕХНОЛОГІЙ ІНДУСТРІЇ 4.0

The paper objective the development of a comprehensive approach to building a resilient supply chain in the food industry using Industry 4.0 technologies is underway. This includes identifying key technologies that can enhance efficiency, transparency, and adaptability of supply chains, as well as providing recommendations and developing steps of implementation a sustainable supply chain in the food industry in accordance with Industry 4.0 principles. The following methods were chosen as an approach to achieve the goal of this research: study and systematization of information on innovative technologies and approaches of Industry 4.0, comparative analysis of the components of these technologies, identification of disadvantages and advantages. Study and analysis of national and international experience of using Industry 4.0 technology in the food industry. This methodology will allow for a comprehensive approach to developing a sustainable supply chain in the food industry, considering both technological and economic aspects. The research finding modern integrations of innovative technologies and Industry 4.0 approaches have been identified for creating a sustainable supply chain in the food industry. A list and key components of modern sustainable supply chain technologies in the food industry have been formulated, advantages and disadvantages of modern sustainable supply chain technologies have been discussed, and national and international experiences in creating sustainable supply chains in the food industry have been determined. Recommendations have been developed for implementing a sustainable supply chain in the food industry in line with Industry 4.0 principles, which require a comprehensive approach covering the assessment of the current state and goals, integration of cutting-edge technologies, development of flexibility, ensuring resilience, environmental responsibility, and active collaboration with partners. Steps have been developed to successfully create a sustainable supply chain in the food industry using Industry 4.0 technologies, focused on the effective implementation of digital initiatives.

Keywords: *Industry 4.0, sustainable supply chain, sustainable development, food industry, the implementation of Industry 4.0 technologies.*

Метою статті є розробка комплексного підходу до створення стійкого ланцюга постачання у харчовій галузі за допомогою технологій Індустрії 4.0. Що включає ідентифікацію ключових технологій, які можуть сприяти підвищенню ефективності, прозорості, адаптивності ланцюгів постачання, а також надання рекомендацій та визначення кроків впровадження стійкого ланцюга постачання у харчовій промисловості відповідно до вимог Індустрії 4.0. В якості підходу для досягнення поставленої мети даного дослідження обрано наступні методи: вивчення та систематизація інформації щодо інноваційних технологій та підходів Індустрії 4.0, порівняльний аналіз складових цих технологій, визначення недоліків та переваг. Вивчення та аналіз вітчизняного та міжнародного досвіду використання

технології Індустрії 4.0 у харчовій промисловості. Дана методологія дозволить всебічно підійти до розробки стійкого ланцюга постачання у харчовій промисловості, враховуючи як технологічні, так і економічні аспекти. Результатом дослідження є визначені сучасні інтеграції інноваційних технологій та підходів Індустрії 4.0 для створення стійкого ланцюга постачання у харчовій промисловості, сформовано перелік та основні складові сучасних технологій стійкого ланцюга постачання у харчовій промисловості, розглянуто переваги та недоліки сучасних технологій стійкого ланцюга постачання у харчовій промисловості, визначено національний і міжнародний досвід створення стійкого ланцюга постачання у харчовій промисловості, сформовано рекомендації щодо впровадження стійкого ланцюга постачання у харчовій промисловості відповідно до принципів Індустрії 4.0, які потребують комплексного підходу і охоплюють оцінку поточного стану та цілей, інтеграцію новітніх технологій, розвиток гнучкості, забезпечення стійкості, екологічної відповідальності, а також активну співпрацю з партнерами. Розроблено кроки для успішного створення стійкого ланцюга постачання у харчовій промисловості з використанням технологій Індустрії 4.0, орієнтованих на ефективну реалізацію цифрових ініціатив.

Ключові слова: *Індустрія 4.0, стійкий ланцюг постачання, сталий розвиток, харчова промисловість, впровадження технологій Індустрії 4.0.*

Formulation of the problem. In the modern world, where globalization and technological progress continuously reshape the economic landscape, the food industry faces a range of challenges regarding ensuring supply chain stability, enhancing production efficiency, reducing environmental impact, and improving product quality. Industry 4.0 technologies offer revolutionary opportunities to address these challenges by providing innovative solutions for creating resilient supply chains in the food industry. Establishing a sustainable supply chain in the food industry becomes increasingly relevant against the backdrop of growing demands for ecological sustainability, production and distribution efficiency, and responsibility.

The utilization of Industry 4.0 technologies enables meeting these requirements while simultaneously ensuring the growth of competitiveness for food industry enterprises. However, despite significant potential, the adoption of Industry 4.0 technologies in the food industry is accompanied by several issues: high implementation costs, the need for workforce retraining, cybersecurity and data protection concerns, as well as risks associated with dependence on high-tech equipment.

Analysis of recent research and publications. The conducted research examined and analyzed works by Ukrainian researchers: S.H. Dubovyk "Supply Chain Management of Enterprises: Essence and Structure" [1]; M.V. Boichenko "Supply Chain Management in the Post-War Period" [2]; I.S. Lutsenko "Closed Supply Chains in the Circular Economy: Effective Inventory Management" [3]; Gryniuk O. "Digital Transformation of Economic Entities in the Context of the Industry 4.0 Concept: Current Trends, Barriers, and Implementation Risks" [4]; I. Mihus "Major Trends in the Development of Industry 4.0 and Its Impact on the Economic Security of the State: International Aspect" [5]; E. Dzhafarova, M. Karpenko "Features and Problems of Implementing Industry 4.0 in Ukraine" [6]; Y.P. Vorzhakova, O.I. Khlebynska "Essence of Digi-tal Transformation from Various Perspectives of Entrepreneurs and Scholars" [7]; A.M. Bortnik "Digital Transformation of Business Models" [8]; V.M. Kudriavtsev "Interconnection of the Digitization Process and the Concept of Sustainable Development" [9]; N. Krasnostanova, T. Yakymenko "Impact of Digitization on the Sustainable Development of an Organization" [10].

Formulation of the purpose of the article. The main goal of this article is to develop a comprehensive approach to creating a resilient supply chain in the food industry using Industry 4.0 technologies. This includes identifying key technologies that can contribute to enhancing efficiency, transparency, and adaptability of supply chains, as well as providing recommendations and developing implementation steps for establishing a sustainable supply chain in the food industry in line with the principles of Industry 4.0.

Presentation of the main material. Before providing a series of recommendations and steps for the effective implementation of a sustainable supply chain in the food industry using Industry 4.0 technologies, let's consider:

1. The peculiarities of integrating innovative technologies and approaches of Industry 4.0 to create a sustainable supply chain in the food industry.

2. Characteristics and key components of advanced technologies for a sustainable supply chain in the food industry in accordance with the principles of Industry 4.0.

3. Advantages and disadvantages of modern technologies for a sustainable supply chain in the food industry according to the principles of Industry 4.0.

4. International and Ukrainian experience in creating a sustainable supply chain in the food industry using Industry 4.0 technologies.

5. Figure 1 illustrates the integration of innovative technologies and approaches of Industry 4.0 for creating a sustainable supply chain in the food industry.

Creating a sustainable supply chain in the food industry using Industry 4.0 technologies (Fig. 1) requires a comprehensive approach to integrating innovative technologies and methods. An important aspect is the implementation of the Internet of Things (IoT), which enables monitoring the condition of products through sensors to ensure their ideal storage and transportation conditions, as well as tracking their movement through the supply chain to ensure transparency. Artificial intelligence (AI) and machine learning are responsible for demand forecasting and logistics optimization, enabling the analysis of large volumes of data to optimize inventory and minimize waste, as well as for selecting the most efficient delivery routes. Blockchain technology ensures the immutability and transparency of transaction records in the supply chain, increasing trust among stakeholders and reducing the level of fraud in external processes, as well as allowing for the certification of product origin.

Digital twins are used to model supply chains and allow for process analysis, identifying weaknesses, and testing potential changes without risking real operations. Automation and robotics significantly increase production efficiency and provide flexibility for quick adaptation to changing market needs. Environmental sustainability, in particular, influences waste reduction and increased energy efficiency, which is a key aspect achievable through process optimization using Industry 4.0 technologies. All the aforementioned elements collectively shape the vectors for creating an efficient, transparent, and environmentally sustainable supply chain in the food industry, leading to cost reduction, improved product quality, and reduced negative environmental impact.

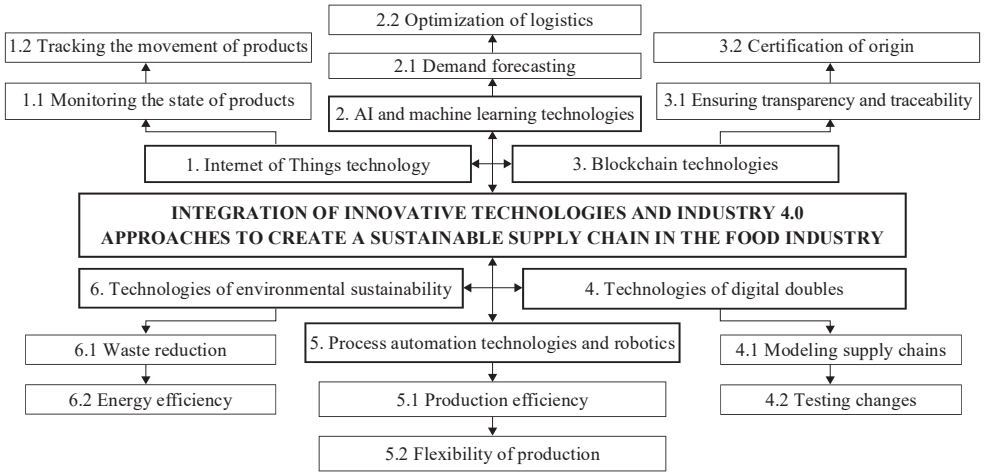

Figure 1. Integration of innovative technologies and approaches of Industry 4.0 for creating a sustainable supply chain in the food industry

Source: formed based on [1–10]

Figure 2 illustrates the characteristics and key components of advanced technologies for a sustainable supply chain in the food industry in accordance with the principles of Industry 4.0.

Based on the data presented in Figure 2, it can be concluded that the implementation of Industry 4.0 technologies in the food industry opens the way for creating innovative models of sustainable supply chains, each of which addresses specific challenges and adds unique value. IoT and blockchain technologies contribute to transparency and security, allowing for precise tracking of product movements and ensuring the immutability of information about them.

This approach not only increases consumer trust but also effectively combats counterfeit products. Demand forecasting based on artificial intelligence (AI) utilizes machine learning algorithms to analyze large volumes of data, enabling accurate demand prediction and inventory optimization, thus minimizing waste and enhancing production planning efficiency.

The application of digital twin technology enables the virtual replication of the supply chain, providing opportunities for detailed analysis and testing of various scenarios without risking real processes, thereby facilitating the identification of weaknesses and system

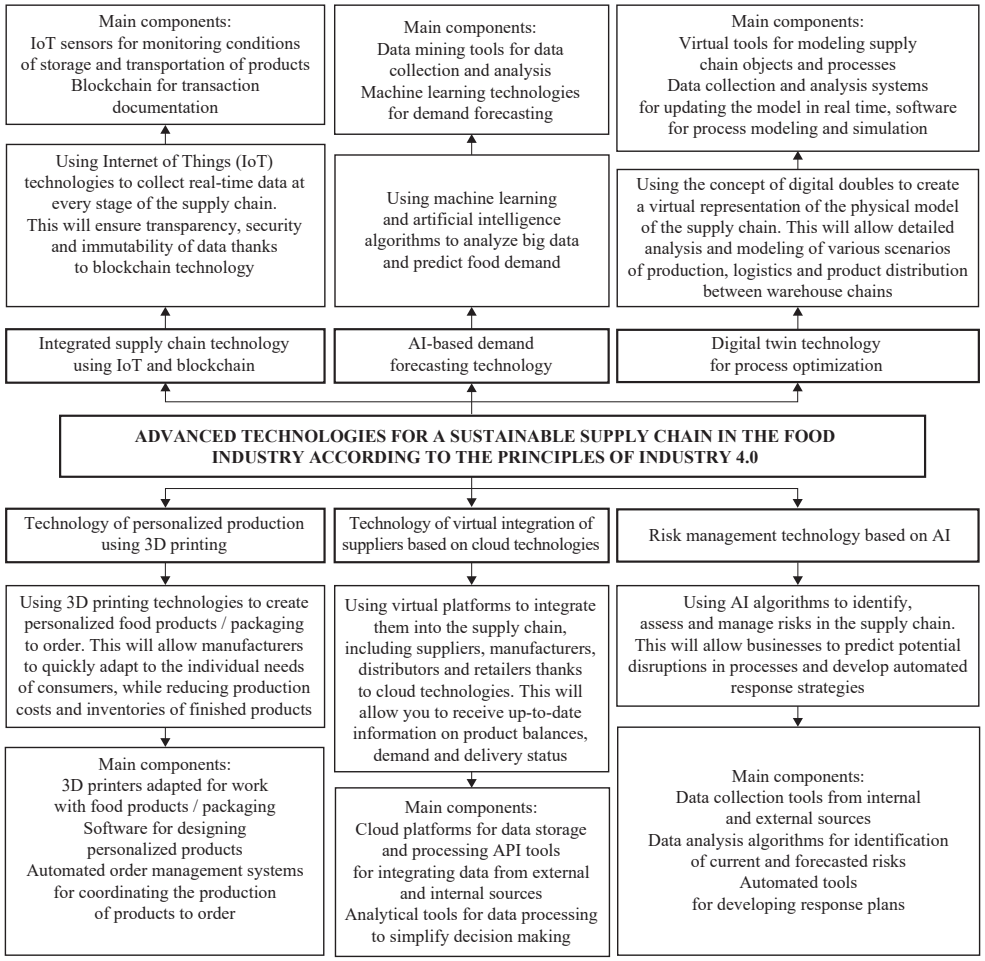

Figure 2. Advanced technologies for a sustainable supply chain in the food industry according to the principles of Industry 4.0

Source: formed based on [1–10]

optimization. AI-based risk management helps identify potential threats to the supply chain and develop effective response strategies, reducing losses and increasing overall system reliability. The implementation of flexible manufacturing using robotics and IoT enhances the adaptability of production lines, allowing for quick adaptation to changing market needs while reducing production costs. Cloud-based virtual supplier integration technology ensures real-time data exchange among all supply chain participants, increasing collaboration efficiency and optimizing logistics. Personalized production technology using 3D printing opens up possibilities for creating unique products according to individual orders, thereby reducing production waste and shortening the time to market for new products. Each of these technologies plays a key role in creating resilient, efficient, and flexible supply chains in the food industry, addressing a range of challenges from process transparency to adaptability and personalization.

Figure 3 outlines the advantages and disadvantages of advanced technologies for a sustainable supply chain in the food industry according to the principles of Industry 4.0.

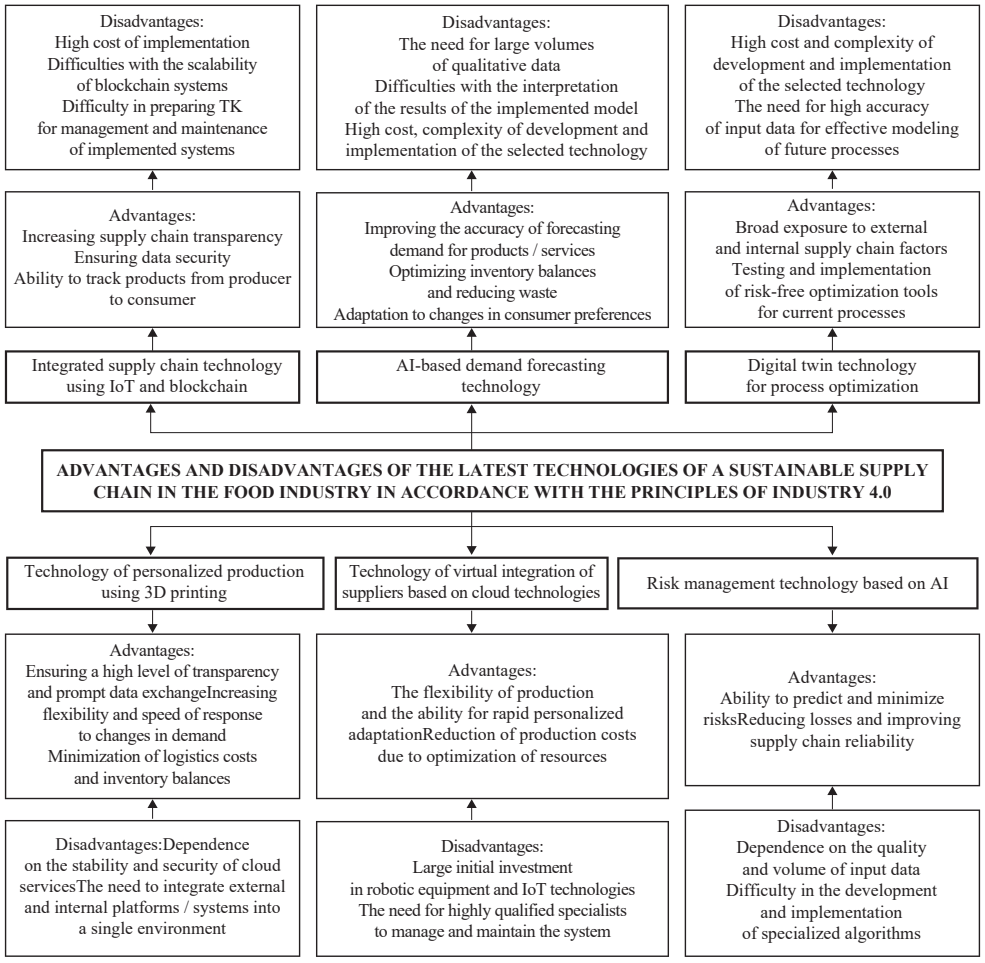

Figure 3. Advantages and disadvantages of advanced technologies for a sustainable supply chain in the food industry according to the principles of Industry 4.0

Source: formed based on [1–10]

The implementation of mechanisms in accordance with the principles of Industry 4.0 in the food industry involves various technologies for creating sustainable supply chains (Figure 3). Each of them has its own advantages and disadvantages. The use of IoT and blockchain technologies enhances transparency and security, but they come with high costs, both in terms of operation and acquisition. Technologies based on artificial intelligence for demand forecasting optimize inventory and reduce waste, but they require large amounts of data. Digital twins allow for detailed analysis of supply chains, but their development entails significant expenses.

Risk management based on AI technologies enhances reliability, while flexible manufacturing using robotics and IoT facilitates rapid adaptation to market changes. Virtual supplier integration through cloud technologies and personalized manufacturing using 3D printing open up new opportunities for optimization and product individualization. Thus, these technologies contribute to enhancing the efficiency, transparency, flexibility, and resilience of supply chains in the food industry, addressing the specific challenges of the sector.

Let's examine the international experience in creating sustainable supply chains in the food industry according to the principles of Industry 4.0:

1. IBM Food Trust collaborates with Walmart to utilize blockchain technologies to create transparent food supply chains. This initiative allows for tracking the origin of products from farmers to consumers, reducing the risk of disease spread, and enhancing consumer trust [15; 16]
2. Nestlé employs AI to analyze large volumes of data and forecast demand for its products. This enables the company to optimize production and inventory, reducing waste and costs [17].
3. Unilever utilizes AI to optimize its supply chains, aiming to reduce environmental impact. The company analyzes data to improve manufacturing processes, reduce water consumption, and carbon emissions [18].
4. Danone utilizes digital twin technology to model and optimize production processes. This allows the company to forecast potential issues, optimize production, reduce costs, and enhance product quality [19].
5. Tyson Foods, a global leader in meat and meat products production, implements IoT technologies for monitoring and controlling production and storage conditions. IoT systems enable the company to ensure high product quality and resource utilization efficiency [20].

The adoption of Industry 4.0 technologies by companies such as IBM Food Trust with Walmart, Nestlé, Unilever, Danone, and Tyson Foods reshapes the future of the food industry, emphasizing the role of innovation in creating sustainable and transparent supply chains. The use of blockchain for product traceability, AI for demand forecasting, and digital twins for production optimization offer new opportunities for waste reduction, quality enhancement, and environmental impact reduction. The utilization of Industry 4.0 technologies, initiatives, and measures significantly contributes to improving food safety and efficiency standards while posing challenges requiring substantial investments and widespread technology adoption. Despite these obstacles, the extensive list of benefits they offer underscores the importance of further integrating innovative solutions into the food industry for a more sustainable and responsible future.

Let's consider Ukraine's experience in creating a sustainable supply chain in the food industry according to the principles of Industry 4.0, using examples of enterprises already utilizing cutting-edge technologies:

1. Agroholding “MHP” – the largest chicken producer in Ukraine and Europe. The company actively implements Industry 4.0 technology, including business process automation, equipment monitoring, and product preservation through IoT devices, and utilizes AI for production optimization [11].
2. PJSC “Kyivkhlib” – a Ukrainian producer of bakery products. The enterprise integrates automated systems for control and management of production processes, including monitoring the quality of raw materials and production efficiency [12].
3. Fozzi Group – a large retail network of offline and online supermarkets, including “Silpo”, “THRASH!”, and “MauDau”. The company actively implements digital technologies to optimize the supply chain, using data for demand analysis and inventory forecasting [13].

4. "Epicenter K" Company – a large retail offline and online network known as a network of building hypermarkets. The company also actively develops its agricultural direction and implements digital technologies to optimize its agricultural projects, including monitoring crop yields and product quality [14].

Thus, Ukrainian companies such as Agroholding "MHP", "Kyivkhlib", "Fozzi Group", and "Epicenter K" have embarked on a course of digital transformation, integrating innovative technologies to enhance efficiency, quality, and resilience of production and supply chains. Agroholding "MHP" and PJSC "Kyivkhlib" utilize IoT technologies for product storage control and AI application for poultry production optimization, bakery automation, and implementing monitoring systems in organic farming. Meanwhile, companies like "Fozzi Group" and "Epicenter K" employ digitization technologies for inventory management. The identified examples of practical use of Industry 4.0 technologies represent the future of the food industry. The existing Ukrainian experience in implementing digitization technologies can serve as an example for other domestic food producers, demonstrating technological solutions that provide real-time product tracking, enhance safety and quality standards, and reduce environmental impact. However, high implementation costs, employee adaptation, and data security remain significant challenges on the path to full digital integration. Despite these obstacles, a commitment to innovation and a desire for improvement lead the Ukrainian food sector to new horizons of efficiency and responsibility, opening doors to the era of a modern, technologically equipped food sector.

On Figure 4, a series of recommendations for companies regarding the implementation of a sustainable supply chain in the food industry according to the principles of Industry 4.0 are provided.

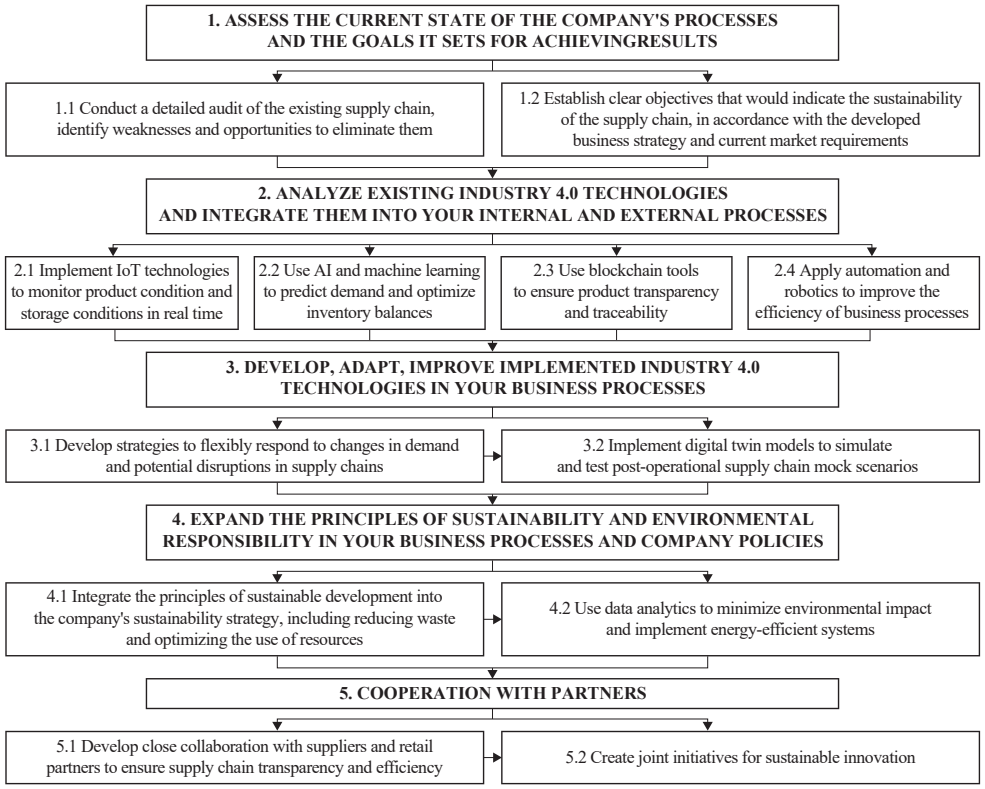

Figure 4. Recommendations for implementing a sustainable supply chain in the food industry in line with the principles of Industry 4.0

Source: developed by the author on the basis of his own research

Adding to the recommendations presented in Figure 4, it can be noted that creating a sustainable supply chain requires a comprehensive approach, including assessing the current state and objectives, integrating advanced technologies, developing flexibility, ensuring resilience, environmental responsibility, and active collaboration with partners. The use of IoT for monitoring, AI for forecasting, blockchain for transparency, and automation for production efficiency contributes to process optimization and waste reduction. Simultaneously, adaptability to changing market conditions and environmental responsibility are crucial for sustainable development.

Effective interaction with suppliers and partners plays a decisive role in creating an innovative, responsible supply chain, opening up new opportunities to enhance quality and meet consumer needs.

Taking into account the results of the conducted research and relying on a series of proposed recommendations (Figure 4), steps have been developed for the creation and implementation of a sustainable supply chain in the food industry using Industry 4.0 technologies, as presented in Figure 5.

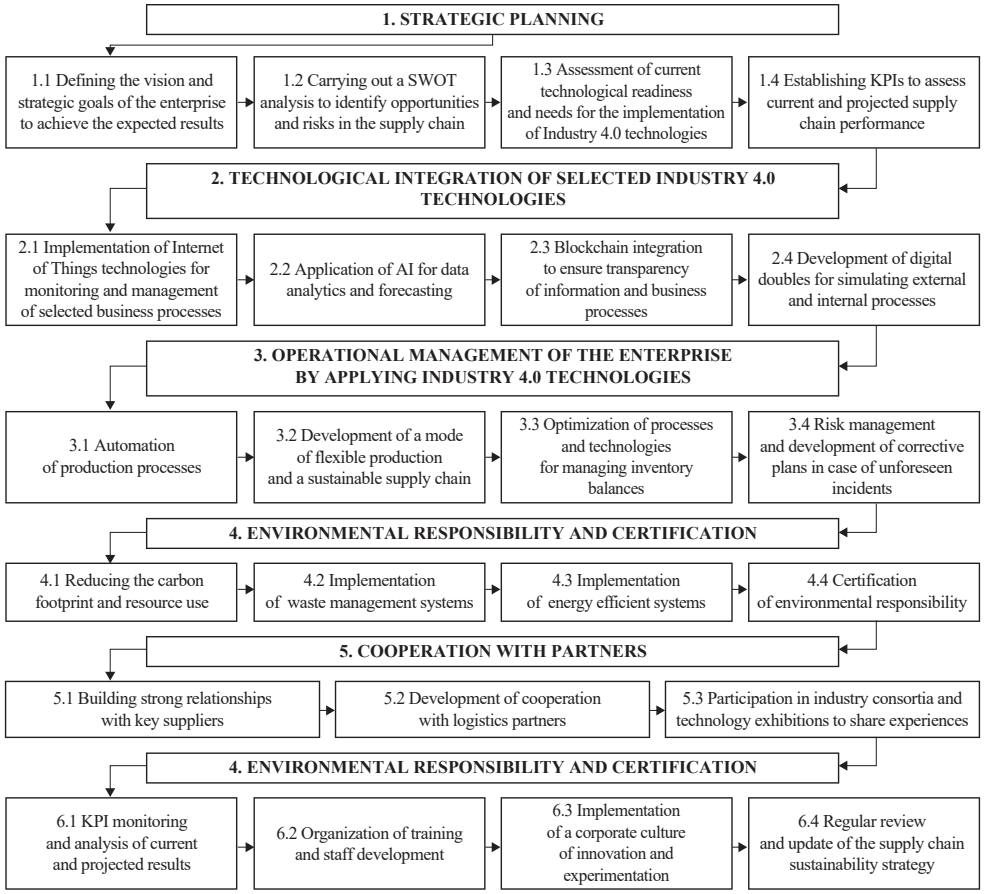

Figure 5. Steps for creating and implementing a sustainable supply chain in the food industry using Industry 4.0 technologies

Source: developed by the author on the basis of his own research

Therefore, to create a sustainable supply chain in the food industry using Industry 4.0 technologies, companies should apply a comprehensive approach that covers processes from strategic planning to continuous improvement. At the initial stage, it is important to conduct a detailed audit of the current state of the supply chain, define the vision, strategic goals, and establish key performance indicators for future assessment. Technological integration requires the implementation of IoT for monitoring the state of production, the use of AI for data analysis, forecasting, blockchain integration to ensure transparency, and the development of digital twins for simulation-based operational forecasting. This will automate internal and external business processes, optimize inventory levels, develop flexible manufacturing models, and risk management.

At the same time, it is important to focus on environmental responsibility, including reducing the carbon footprint, implementing waste management systems, and certifying environmental responsibility by the company. Collaboration and partnership with key suppliers, logistics partners, participation in industry consortia play an important role in innovation development, increasing supply chain resilience, and competitiveness. Equally important will be the application of continuous improvement procedures through regular monitoring of post-operational KPIs, organizing training for personnel, implementing a corporate culture of innovation and experimentation, and regular review and updating of the strategy to ensure long-term efficiency and sustainability of the supply chain.

Conclusions. Therefore, creating a sustainable supply chain in Ukraine's food industry using Industry 4.0 technologies requires an integrated approach that combines strategic planning, technological integration, operational management, environmental responsibility, and collaboration with partners. Success lies not only in the implementation of individual technologies but also in their synergy and adaptation to the specific needs and capabilities of Ukrainian companies. Ukrainian experience indicates successful application of Internet of Things (IoT) in the agroholding "MHP" for equipment monitoring and poultry production optimization. "Kyivkhlib" uses automated systems for monitoring raw material quality, ensuring high product standards. Large retail companies such as "Fozzi Group" and "Epicenter K" apply digital technologies for supply chain optimization, using data for demand analysis and inventory forecasting. International experiences of companies like "IBM Food Trust" and "Walmart" demonstrate that blockchain can provide transparency in the food supply chain from farmer to consumer. Companies like "Nestlé" and "Unilever" actively implement AI to optimize supply chains, improving production efficiency and reducing environmental impact. The formulated recommendations for implementing a sustainable supply chain in the food industry according to the principles of Industry 4.0 focus on auditing existing digital systems and the state of external and internal business processes, setting clear goals based on SWOT analysis, integrating IoT for real-time operational monitoring, using AI for data processing and analysis, blockchain for transparency, and developing digital twins for more effective risk management and process optimization. The developed steps for implementing a sustainable supply chain encompass not only technological integration but also emphasis on flexibility, adaptability, environmental responsibility, close collaboration with partners, continuous improvement through post-operational KPI monitoring, personnel training, and regular strategy review. All these efforts are aimed at achieving the main goal – creating an efficient, transparent, and environmentally sustainable supply chain that meets modern requirements and standards, both in the international and national markets..

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