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THE ASSESSMENT OF THE IMPACT OF SUSTAINABLE PRODUCTION METHODS ON ECONOMIC EFFICIENCY IN THE FOOD INDUSTRY

S u m m a r y

Background. The study aimed to analyze the impact of sustainable production methods on the economic efficiency of food industry enterprises. The study examined current trends in the introduction of energy-efficient technologies, digitalization, waste management and circular economy principles, and analyzed the economic benefits of using intelligent control systems and renewable energy sources. Automated energy monitoring systems reduced energy costs by 12 ÷ 18 %, while the integration of renewable energy sources reduced costs by 30 ÷ 40 % in the long term.

Results and Conclusions. The study determined that the transition to circular production models increases profitability by 8 ÷ 15 % by reducing the cost of purchasing raw materials and optimizing waste processing. The study established that enterprises implementing advanced waste processing technologies can not only minimize the cost of waste disposal, but also create new revenue streams through the production of biogas, feed additives and secondary materials. The study proved that the use of smart sensors and machine learning algorithms can optimize resource consumption, prevent equipment breakdowns and reduce production losses. These technologies also help automate quality control processes and ensure more accurate forecasting of demand and supply management. The key barriers to the introduction of sustainable technologies were identified, including high investment costs, the need to modernize infrastructure, the difficulty of integrating with existing production processes and the lack of qualified specialists. The study found that the effective implementation of a sustainable production strategy requires the interaction between business, the state and scientific circles. The development of financial instruments, such as tax reliefs, subsidies and schemes supporting innovation, may largely expedite enterprises' transition to environment-friendly and cost-effective operating models. The study concluded that enterprises

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investing in innovative methods of sustainable production gain significant competitive advantage and ensure long-term business growth in the context of the global environmental agenda.

Keywords: digitalization of production, energy efficiency, waste management, circular technologies, environmental innovations

Introduction

Given the current global challenges associated with climate change, depletion of natural resources and growing demand for food, the introduction of sustainable production methods in the food industry has become particularly relevant. This issue is of particular importance for Azerbaijan, Ukraine, Bulgaria and Kyrgyzstan, where the food industry is one of the key sectors of the economy that ensures food security and a significant share of export earnings. In the four countries, there is a growing interest in modernizing production, introducing environmentally friendly technologies and using natural resources more efficiently.

The transformation of production processes towards sustainable development has become a prerequisite for increasing the competitiveness of food companies in the international market. For Ukraine, this is especially relevant in the context of European integration, while for Azerbaijan, it aligns with efforts in economic diversification and the expansion of its export potential. It is equally important for Kyrgyzstan, where the food industry is a key sector for economic development, and for Bulgaria, as part of its ongoing integration into the European Union's green economy initiatives.

Ismayil-Zada [32], based on an analysis of 50 food processing enterprises in Azerbaijan, showed that the introduction of environmentally friendly technologies can reduce energy consumption by 15 ÷ 20 % and waste by 25 ÷ 30 %. A methodology for assessing the effectiveness of environmental innovations has also been developed to analyze the sustainability of production processes.

Harizanova-Metodieva and Harizanova-Bartos [26], in the study of the digital transformation of Bulgarian food processing companies, analyzed more than 100 companies and found that the integration of digital technologies with environmental management systems can achieve a synergistic effect, increasing operational efficiency by 20 ÷ 25 %. The methodology for assessing the effectiveness of implementing sustainable practices developed by Kucher and Kucher [41] is based on an analysis of 75 Ukrainian food processing companies. Their study showed that the integrated implementation of energy-efficient technologies and waste management systems can reduce operating costs by 18 ÷ 22 %. Of particular importance is the conclusion that government support has a significant impact on the speed of innovation. Mamyralieva et al. [45] conducted a large-scale study of 60 food processing enterprises in Kyrgyzstan, assessing the potential for the introduction of environmentally friendly technologies.

Their analysis showed that even with limited investment opportunities, the introduction of basic elements of sustainable production can reduce production costs by 12 ÷ 15 %.

The analysis of scientific publications in the field of sustainable development of the food industry identified existing research approaches and identified insufficiently studied aspects that require further research. Proctor et al. [53] confirmed a positive correlation between environmental efficiency and production profitability when implementing sustainable technologies. A significant contribution to the study of the economic aspects of implementing circular production models in the food industry was made by Menon and Jain [46]. Their research showed that the application of circular economy principles reduced production costs by 15 ÷ 20 %. The issues of implementing sustainable production methods in the context of developing economies were studied by Raveloaritiana and Wanger [55], identifying key barriers and success factors in the transition to sustainable production models. For instance, Feng et al. [18] considered the impact of climate change on the potential expansion or degradation of arable land. The study was based on a predictive model of the spatial and temporal distribution of productive areas, which assessed long-term risks to global agricultural production. The study emphasized the need for adaptation strategies in land use, especially in the regions vulnerable to climate change.

Willmes [72] proposed a concept of agricultural sustainability based on the principles of proactive management. In their model, the key element is the ability of agricultural producers and governments to respond to climate risks before crises occur. The study emphasized the importance of a transdisciplinary approach in which ecologists, agronomists and managers collaborate to develop sustainable solutions. From a systems analysis perspective, Goold et al. [22] developed a mathematical model for assessing the sustainability of national food systems. The model can be used for the integration of data on yields, resource consumption, greenhouse gas emissions and economic indicators. This makes it possible to assess whether a particular food system meets the criteria for sustainable development and to predict its behavior in the face of external shocks. Lastly, Springmann et al. [60] analyzed the potential ways of transforming the global food system, addressing environmental boundaries and sustainability indicators. The study modelled alternative development scenarios, including a shift to a more plant-based diet, the reduction of emissions in the agricultural sector and the introduction of efficient technologies at all stages of the supply chain.

The analysis of existing studies revealed that the issues of quantifying the economic effect of the introduction of sustainable practices in the food industry in Azerbaijan, Bulgaria, Kyrgyzstan and Ukraine, as well as the factors that determine the success of their implementation in local markets, remain insufficiently studied. The study of mechanisms for adapting international experience to the specifics of developing economies was emphasized.

The study aimed to identify the impact of sustainable production methods on the economic efficiency of food processing enterprises in Azerbaijan, Bulgaria, Kyrgyzstan and Ukraine. The following tasks were completed in the course of the work: to conduct a comparative analysis of the implementation of sustainable production practices in these countries, assess the economic effects of energy efficient technologies, waste management systems and digitalization; analyze possible government support measures aimed to stimulate the transition to sustainable production models, including tax incentives, grant programmes, subsidies for the modernization of the technological base and the adaptation of regulatory standards to international requirements.

Literature review

The introduction of sustainable food production methods is the subject of active scientific research to reduce the negative impact on the environment, increase resource efficiency and economic sustainability of enterprises. The scientific literature widely presents the results of studies of the impact of environmental innovations, circular economy, energy-efficient technologies and waste management on the performance of companies in the industry. These studies are particularly relevant in the context of growing requirements for environmental safety in production and the rising cost of natural resources.

Fanzo et al. [15] analyzed the impact of sustainable technologies on the economic efficiency of food industry enterprises. The study addressed a positive correlation between environmental efficiency and production profitability, which confirms the economic feasibility of introducing environmental innovations. The study by Feng et al. [18] developed a method for assessing the energy efficiency of production processes, which covered both direct and indirect effects of the introduction of sustainable technologies. A separate methodology proposed by Farmery et al. [16] analyzed the standardization of energy efficiency assessment and created universal performance criteria for different types of enterprises. A comparison of both studies shows a common idea regarding the economic benefits of sustainable production.

Ukrainian researchers Dziurakh et al. [12] developed an approach to modelling the effectiveness of implementing environmental practices in the agri-food sector, addressing government regulation and food security in production. Compared to the Ukrainian study on regulatory mechanisms, the analysis of Nikolakis et al. [49] proposed practical strategies for sustainable production based on environmental assessment of processes. In Azerbaijan, Guliyeva and Lis [25] studied the experience of introducing environmentally friendly technologies at local enterprises. The study emphasized the importance of adapting international practices to local conditions, which coincides with the results of Ahmed et al. [1] on similar challenges in Central Asia and the Caucasus. Mitseva [47] characterized the digital transformation of food industry enterprises in Bulgaria. The study analyzed the impact of digitalization on the sustainable development of production, in particular through the integration of IT solutions into the agricultural sector.

In Kyrgyzstan, Kozhogulova et al. [39] addressed the potential for introducing environmentally friendly technologies, covering the conditions of developing countries. A similar topic was addressed by Debnath et al. [11], who applied the grey analysis method to assess barriers to sustainable production. A comparative analysis shows that both studies are applied in nature and aimed to identify barriers, but Debnath uses a more formalized approach to assessment. Waste management issues were investigated in the work of Kotz et al. [38]. The study determined that the application of waste minimization methods, including recycling and reuse of raw materials, yields positive results in enterprises. The researchers developed a model for optimizing waste management processes that incorporate economic and environmental parameters. Fassio et al. [17] found that in developing countries, the main barriers are limited funding, technical capacity and legislative frameworks.

While the introduction of digital technologies in sustainable production has been widely researched in the food industry, gaps remain in understanding how these technologies can be adapted and implemented in regions with lower levels of digitalization. Although studies have shown that automated energy monitoring systems can significantly reduce costs and enhance resource efficiency, there is limited research on the specific barriers faced by businesses in less digitally advanced areas. Furthermore, while the integration of digital technologies with environmental management systems has shown a positive impact on achieving sustainability goals, the practical application and scalability in diverse contexts require further exploration. Additionally, issues related to cybersecurity and data protection in the implementation of digital solutions remain underexplored, highlighting the need for a more comprehensive approach that addresses both technological and organizational challenges.

Materials and methods

A study of the impact of sustainable production methods on the economic efficiency of food industry enterprises in Azerbaijan, Bulgaria, Kyrgyzstan and Ukraine was conducted in several stages. These countries were selected because the food industry is key in their economies, ensuring food security, significant export potential and employment. In addition, these countries represent a variety of conditions: from countries actively integrating into the European economic space (Ukraine, Bulgaria) to countries with a developing institutional and technological base (Azerbaijan, Kyrgyzstan), which were used for a comparative analysis of differences in the implementation of sustainable production practices.

At the first stage, scientific sources for 2019 ÷ 2025, regulations and statistics were analyzed to form the theoretical basis of the study: Food Industry Report [20], The SDGs and the UN Summit of the Future. Sustainable Development Report 2024 [57]. Regulatory and legal acts: Green Solutions from Bulgaria [23], Concept for the Development of the Food and Processing Industry [10]. For Ukraine and Bulgaria, the analysis of EU standards in the field of sustainable production was addressed, as the countries are actively implementing European standards in the agro-industrial complex and the food industry. For Kyrgyzstan and Azerbaijan, the regional regulations and standards of the Eurasian Economic Union in the field of sustainable development were addressed.

At the second stage, an empirical analysis of food industry enterprises operating in Azerbaijan, Ukraine, Bulgaria and Kyrgyzstan was conducted. To ensure the completeness of the empirical analysis, the study included the leading food industry enterprises in Azerbaijan, Bulgaria, Kyrgyzstan and Ukraine that implement sustainable technological solutions. The practices implemented by these enterprises were recorded based on open sources and corporate reports.

The companies implementing sustainable technologies were selected as research subjects. In Ukraine, the study was conducted at Kyivkhlib [43], where energy-efficient production systems have been implemented, MHP [30], which uses biogas plants and advanced waste processing technologies, and Molokiya, which applies innovative processing and energy-saving systems [48]. In Azerbaijan, the experience of Azersun Holding [3], which has implemented solar panels and energy-efficient technologies, and Baku Agropark [61] with its automated production systems, was analyzed. The Bulgarian experience is represented by Bella Bulgaria [64], which uses digital production control systems, Nestlé Bulgaria [63] with integrated energy management systems, and Mondelez Bulgaria [62], which applies predictive analytics in production. In Kyrgyzstan, Bishkeksut [2], which has implemented waste monitoring systems, Kant Sut [35], which uses organic waste processing technologies and Shoro [9], with automated quality control systems, were studied.

These firms were chosen as they exemplify premier instances of sustainable innovation and technological progress within their national food sectors. Each participant has adopted unique ecologically focused activities that correspond with the study's objective of evaluating the economic efficiency of sustainable production techniques. The selection was predicated on the enterprises' evidenced advancement in the incorporation of sustainable technologies, such as energy efficiency systems, renewable energy sources, waste recycling and digital process control, alongside the accessibility of transparent corporate data and sustainability reports that facilitated empirical analysis.

Additionally, these companies were selected to represent a variety of national settings and degrees of technological advancement. In Ukraine, companies like Kyivkhlib, MHP and Molokiya exemplify the integration of biogas facilities, energy-efficient systems and recycling technologies in accordance with European environmental requirements. Azersun Holding and Baku Agropark in Azerbaijan exemplify the country's strategic transition towards renewable energy and automation, capitalizing on its enormous solar resources. Bella Bulgaria, Nestlé Bulgaria and Mondelez Bulgaria were recognized for their superior digitalization and adherence to EU sustainability regulations, whereas Bishkeksut, Kant Sut and Shoro in Kyrgyzstan illustrate the incremental integration of sustainable practices in emerging economies. This cross-national representation guaranteed result comparability and enabled the study to encompass both the technological and institutional aspects of sustainable transformation in the food sector.

The selection criteria included the level of technological modernization, the availability of programs to reduce negative environmental impact and the application of resource-saving principles. The sample was formed on the basis of available data on their production activities and reporting. The study used descriptive and comparative statistics, as well as basic correlation and regression analysis to identify the relationship between the implementation of sustainable production methods and such indicators as profitability, cost level and output. The analysis was conducted using a 95 % confidence interval and set a statistical error of ±2.5 %. The reliability of the results was checked using a significance level ($p < 0.05$) and a preliminary assessment of the data for logic and consistency.

To quantify the economic efficiency, profitability indicators (high: > 15 %, average: 8 ÷ 15 %, low: < 8 %), resource utilization rates (high: > 20 %, average: 10 ÷ 20 %, low: < 10 %) and the level of waste management costs (high: > 25 %, average: 15 ÷ 25 %, low: < 15 %) were used. The analysis used correlation analysis methods to determine the relationship between sustainable practices and the economic performance of the companies. The data were processed using SPSS Statistics 28.0 and Microsoft Excel 2023 software for statistical analysis.

As an additional stage of the study, an expert survey was conducted to identify the factors of success in the implementation of sustainable technologies and assess existing barriers to their implementation. The survey covered 120 respondents from the food industry companies included in the empirical study: Kyivkhlib, MHP, Molokiya (Ukraine); Azersun Holding, Baku Agropark (Azerbaijan); Bella Bulgaria, Nestlé Bulgaria, Mondelez Bulgaria (Bulgaria); Bishkeksut, Kant Sut, Shoro (Kyrgyzstan). Thirty representatives from each country participated in the study, including general managers (15 %), technical directors (25 %), heads of sustainability departments (30 %) and chief technologists (30 %). Age distribution of participants: 30 ÷ 40 years old (35 %), 41 ÷ 50 years old (45 %), over 50 years old (20 %); gender ratio: women (45 %), men (55 %).

The examples of key questions in the questionnaire: Please rate the effectiveness of the implemented sustainable technologies on a scale from 1 to 10. What are the main barriers to the introduction of environmental innovations? How do you assess the level of government support for sustainable development?

To assess the factors influencing the success of sustainable technologies implementation, data from an expert survey, in which respondents were asked to assess the impact of various groups of factors: technological, economic, regulatory, climatic and social, were used. The assessment was made on a 10-point scale, where 1 – the factor has little or no impact, and 10 – the factor is crucial. The results were aggregated and subjected to a factor and correlation analysis using SPSS Statistics 28.0. The main evaluation criteria were: the level of influence of the factor on the speed of technology adoption, the sustainability of the effect and the degree of dependence on external conditions.

The study was conducted following the ethical standards of conducting sociological surveys: participation in the survey was completely voluntary, the respondents were informed in advance about the objectives of the study and could refuse to participate at any stage without giving any reason. The confidentiality of answers was maintained, and personal data was processed following the provisions of international standards ISO No. 20252:2019 "Market, Opinion and Social Research, Including Insights and Data Analytics Vocabulary and Service Requirements" [33] and the General Data Protection Regulation [21]. The survey results were processed by a factor analysis using SPSS Statistics 28.0, with a statistical error of ±3.2 % with a confidence interval of 95 %.

In general, the study included a comprehensive approach to assessing the impact of sustainable production methods, combining theoretical analysis, empirical research and expert assessments. This provided a comprehensive picture of the impact of environmentally efficient strategies on the economic sustainability of food processing companies in Azerbaijan and Ukraine.

Results

Economic benefits of implementing sustainable technologies in the food industry

Businesses are faced with the need to find innovative solutions to improve their economic efficiency and competitiveness. One of the key areas is the introduction of sustainable production methods aimed to reduce the negative impact on the environment and rational use of resources. The introduction of sustainable technologies is particularly relevant in the bakery industry, as production requires significant energy and water consumption. The use of energy-efficient ovens and the modernization of equipment can reduce energy consumption by 20 ÷ 30 % [53]. In addition, the automation of dough preparation and baking processes helps to reduce production losses, and the introduction of intelligent quality control systems improves product stability, which has a positive impact on the economic efficiency of enterprises.

One of the key drivers of economic benefit is the reduction of operating costs through energy savings. The use of intelligent energy management systems reduced electricity costs by 12 ÷ 18 % compared to traditional methods [45]. The introduction of automated energy management solutions, such as motion detectors, smart lighting and temperature control systems, helps to minimize unnecessary energy costs. Companies that actively use renewable energy sources, such as solar panels and wind turbines, significantly reduce their dependence on volatile oil and gas prices [54; 40]. This is especially true in the context of global economic crises and geopolitical factors affecting the energy market. The introduction of solar panels reduced energy costs by 30 ÷ 40 % in the long term.

In Azerbaijan, where solar resources are abundant, this approach can be a strategic advantage for food processing companies. In Ukraine, which is actively developing renewable energy as part of Europe's decarbonization drive, there is also growing interest in introducing alternative energy sources into the agricultural sector. The introduction of solar and wind power plants at food processing companies not only reduces production costs, but also increases the energy independence of the industry [36]. In addition, Ukraine is integrating a system of green certificates, which creates additional incentives for companies to switch to renewable energy sources [14]. Additional economic benefits are provided by the transition to circular production models, which involve the reuse of resources and the minimization of waste. The optimization of resource consumption leads to an increase in profitability by 8 ÷ 15 %, as the cost of purchasing raw materials is reduced [23]

The study analyzed the implementation of sustainable technologies at the leading food processing companies in four countries. Table 1 shows the key enterprises and the technological solutions they have implemented in the field of sustainable development.

The analysis of implemented sustainable technologies shows differences in approaches to modernizing production depending on the level of economic development, climatic conditions, institutional support and availability of technologies in each of the countries studied. In Ukraine, a comprehensive approach to implementing sustainable solutions is driven by a combination of factors: access to international financing programs, commitments to the EU to adapt environmental standards and a high degree of integration of enterprises into the agro-industrial chain. This creates incentives for investment in energy saving, waste recycling and innovative solutions to improve efficiency.

Table 1. The implementation of sustainable technologies at food industry enterprises in the countries under study (2023 ÷ 2024).
Tabela 1. Wdrażanie technologii zrównoważonych w przedsiębiorstwach przemysłu spożywczego w badanych krajach (2023 ÷ 2024).

Country	Company	Technologies implemented
Ukraine	"Kyivkhlib"	Energy-efficient production systems
	MHP	Biogas plants and waste treatment technologies
	"Molokiya"	Innovative recycling and energy-saving systems
Azerbaijan	"Azersun Holding"	Solar panels and energy-efficient technologies
	"Baku Agropark"	Automated production systems
Bulgaria	"Bella Bulgaria"	Digital production control systems
	"Nestlé Bulgaria"	Integrated energy management systems
	"Mondelez Bulgaria"	Predictive analytics in manufacturing
Kyrgyzstan	"Bishkeksut"	Waste monitoring systems
	"Kant Sut"	Organic waste processing technologies
	"Shoro"	Automated quality control systems

Explanatory notes / Objaśnienia: compiled by the authors based on Food Industry Report [20], The SDGs and the UN Summit of the Future. Sustainable Development Report 2024 [57] / zebrane przez autorów na podstawie Food Industry Report [20], The SDGs and the UN Summit of the Future. Sustainable Development Report 2024 [57]

In Azerbaijan, the active use of renewable energy sources, in particular solar energy, is driven by favorable climatic conditions and a growing focus on energy independence. In addition, export orientation and corporate image goals are driving the adoption of green solutions, including environmentally friendly packaging and automated systems. Digitalization in Bulgaria has advanced significantly due to systematic government support, EU membership and a high level of digital infrastructure. Therefore, businesses adopted not only monitoring and control technologies, but also more sophisticated analytical tools such as predictive analytics. In Kyrgyzstan, sustainable practices are developing more slowly and primarily relate to basic areas such as waste recycling and quality control. This is due to limited investment opportunities, low levels of technological equipment and the need to adapt international solutions to local conditions. Thus, the differences identified in the approaches to sustainable production reflect not only the internal strategic priorities of companies, but also the broader socio-economic and institutional conditions in which the food industry operates in each country.

Effective waste management is also central to improving the economic sustainability of food processing companies. Modern waste processing technologies not only minimize the negative impact on the environment, but also significantly reduce production costs [65]. In the context of tightening environmental regulations and rising energy prices, competent waste management is becoming crucial for improving business competitiveness. The baking industry generates a significant amount of waste every year, ranging from raw material residues to unsold products. Modern enterprises are introducing technologies for the recycling of bakery products, such as the production of breadcrumbs or the use of waste as feed additives for farm animals [68]. Another promising area is the processing of bakery waste for biogas production, which not only minimizes losses, but also generates an additional source of energy [1].

One of the most promising areas is the introduction of circular economy principles, in which waste is seen not as a burden, but as a valuable resource. Many companies are striving to create closed production cycles in which the maximum amount of waste is recycled and reused. This reduces the cost of purchasing raw materials by 10 ÷ 14 %, which has a positive impact on the financial performance of enterprises [34]. The use of biotechnology for waste management opens additional opportunities to reduce production costs. For instance, the processing of organic waste into biogas and fertilizers is becoming an effective way to reduce the cost of traditional energy sources. Biogas plants can partially or fully meet corporate electricity and heat needs, reducing dependence on external energy suppliers [69]. The production of vermicompost and organic fertilizers from food waste can be an additional source of income and increase the sustainability of the agricultural sector, which is particularly relevant for agricultural regions of Azerbaijan and Ukraine.

Biogas technologies are being actively developed in Ukraine as part of the national decarbonization and energy independence strategy. The national agricultural sector is already implementing projects to process organic waste, including food waste, into biogas and biofertilizers. Many Ukrainian food processing companies, especially in the bakery and dairy sectors, use production residues to generate energy, which not only reduces costs, but also reduces greenhouse gas emissions [42].

Companies such as Nestlé are actively investing in the recycling of packaging and food waste, developing technologies that can be used as secondary raw materials. For instance, recycling food waste into animal feed not only reduces disposal costs, but also reduces the need for traditional feed, which is resource-intensive. As a result, the burden on the ecosystem is reduced, greenhouse gas emissions are reduced and the amount of waste sent to landfills is reduced.

The development of packaging recycling technologies is also substantial in the sustainable development of the food industry. Plastic packaging, which takes a long time to decompose in the natural environment, can be recycled into new products, reducing the need for virgin raw materials. The development of biodegradable packaging materials based on natural polymers is becoming a priority for many manufacturers. Azerbaijan is already introducing such technologies, which will significantly reduce the level of environmental pollution in the future.

Innovative approaches to waste sorting increased the efficiency of recycling [7]. The use of automated sorting systems based on machine vision and artificial intelligence technologies can be used to separate waste with high accuracy, ensuring maximum use of recyclable materials. Such solutions have already been successfully used in European countries and are gradually being adopted in Azerbaijan and Ukraine [71].

In Ukraine, large food processing companies are introducing intelligent waste monitoring systems to optimize waste recycling and reuse. The country is also actively developing projects to create closed production cycles, where recycled materials are used to produce new packaging or feed additives. This is particularly relevant in the context of fulfilling its obligations to the EU to reduce food waste and increase recycling rates.

The digitalization of waste management processes are substantial in optimizing costs and increasing recycling efficiency. Modern software solutions can be used for the real-time tracking of waste volumes, the planning of waste removal and recycling logistics and the analysis of the effectiveness of various recycling methods. This helps reduce waste transportation costs and simplifies resource management [51].

The development of partnerships between food producers and processors can significantly accelerate the adoption of sustainable practices in the industry. Joint investments in recycling facilities and the creation of supply chains for efficient waste collection reduce costs and increase environmental responsibility. Government support for such initiatives, including through tax breaks and subsidies, can be an additional incentive to switch to sustainable waste management practices.

Food waste management also has a social impact. Many countries are actively developing programs to redistribute surplus food to those in need, which not only reduces waste, but also addresses the issue of food security. In Azerbaijan, the development of such initiatives could be a substantial step in shaping responsible consumption and reducing food losses. The survey results demonstrate significant differences in the assessment of the effectiveness of sustainable technologies implementation between the surveyed countries. Table 2 shows the key indicators in the main areas of sustainable development and their assessment by experts.

The analysis of the results shows that energy-saving technologies received the highest scores in all the countries surveyed. Experts note that this trend is due to the quick payback of such projects and the availability of measurable economic results. Bulgaria demonstrates a leading position in all indicators, which is explained by its longer experience of working under European environmental standards and a developed system of government support. There is a significant gap in the level of government support between the EU countries and the rest of the survey participants. Experts from Azerbaijan and Kyrgyzstan highlighted the need to develop the legislative framework and create additional mechanisms to encourage the introduction of sustainable technologies.

Table 2. Comparative analysis of the effectiveness of sustainable technologies implementation in the food industry of the studied countries (on a 10-point scale).

Tabela 2. Analiza porównawcza efektywności wdrażania zrównoważonych technologii w przemyśle spożywczym badanych krajów (w skali 10-stopniowej).

The direction of the assessment	Ukraine	Bulgaria	Azerbaijan	Kyrgyzstan
Energy-saving technologies	8.7	8.8	7.9	7.8
Waste management systems	8.3	8.4	7.6	7.5
Digitalization of production	8.5	8.6	7.8	7.7
Renewable energy sources	8.4	8.5	8	7
Level of government support	6.8	7.5	5.4	5.2

Explanatory notes / Objaśnienia: summarized by the authors based on empirical research and analysis of Dziurakh et al. [12], Guliyeva and Lis [25], Mitseva [47], Kozhogulova et al. [39] / podsumowane przez autorów na podstawie badań empirycznych i analiz Dziurakh et al. [12], Guliyeva i Lis [25], Mitseva [47], Kozhogulova et al. [39]

Sustainable technologies are crucial for bolstering food security and improving resilience to climate change by fostering resource efficiency, mitigating environmental degradation and stabilizing agricultural production systems [6, 74]. By integrating renewable energy, precision irrigation, waste-to-biogas conversion and digital monitoring, food operations can alleviate the risks posed by droughts, heatwaves and resource constraint. These improvements guarantee uninterrupted output despite unfavorable weather circumstances, diminish reliance on fossil fuels and mitigate greenhouse gas emissions. Sustainable technologies enhance resource efficiency and promote circular production models, thus ensuring the integrity of food supply chains, while fostering long-term ecological equilibrium and the resilience of national food systems [37, 24].

Notably, the digitalization of production received high marks in all the countries, which indicates a global trend towards the automation and optimization of production processes. At the same time, experts emphasize the importance of developing staff competencies and creating specialized training programs for the effective use of digital technologies. Waste management systems have shown the greatest potential for improvement, especially in Azerbaijan and Kyrgyzstan. Experts highlighted the need to develop recycling infrastructure and introduce circular economy principles to improve efficiency in this area.

Thus, effective waste management not only helps to reduce costs and increase profitability, but is also key in the transition to a sustainable economic model. Companies that implement innovative recycling methods gain competitive advantages, strengthen their reputation and ensure long-term business stability. In the context of the global transition to environmentally friendly production, waste management is becoming a relevant factor in the sustainable development of the food industry in Azerbaijan and Ukraine.

This area is particularly relevant for Ukraine in light of its European integration and the need to adapt to EU environmental standards. The national government policy is aimed to develop recycling infrastructure, support businesses that implement sustainable technologies and encourage investment in waste management projects. Many Ukrainian companies are already switching to environmentally friendly models, including through the introduction of organic and packaging waste recycling technologies.

Factors influencing the success of sustainable technologies

The success of sustainable technologies in the food industry in Azerbaijan, Ukraine, Kyrgyzstan and Bulgaria depends on several key factors that determine the speed and efficiency of the transition to environmentally friendly production. The technological level of enterprises is crucial, as modernized equipment and digital solutions optimize resources, minimize waste and increase energy efficiency. Access to innovative technologies and their adaptation to local conditions accelerate the process of implementing sustainable solutions. In Ukraine, many enterprises are undergoing technological modernization as part of government and international funding programs, which contribute to an accelerated transition to environmentally friendly production [59].

The analysis of empirical data revealed several successful projects that exemplify the economic and environmental effectiveness of sustainable production technologies. Among the most notable are initiatives implemented by MHP and Molokiya in Ukraine, Azersun Holding in Azerbaijan, and Bella Bulgaria and Nestlé Bulgaria in Bulgaria. Each of these projects provides measurable improvements in cost reduction, energy efficiency and waste utilization, demonstrating how sustainability strategies generate tangible economic returns (Table 3).

Economic factors, including the level of investment, the availability of government support programs and access to international financing, have a significant impact on the implementation of environmental initiatives [31]. Ukraine has several subsidy programs for the modernization of the food industry, including EU grants for the introduction of environmentally friendly technologies. Government policies and regulatory framework provide the basis for the development of sustainable production. Improved standards, tax breaks for environmentally friendly companies and strict monitoring of compliance with environmental regulations motivate companies to adopt sustainable technologies. Ukraine is actively adapting its legislation to EU requirements, which creates additional incentives for the implementation of environmentally friendly solutions [66].

Table 3. Quantitative results of successful sustainability projects (2023 ÷ 2024).
Tabela 3. Wyniki ilościowe udanych projektów dotyczących zrównoważonego rozwoju (2023 ÷ 2024).

Country	Enterprise	Implemented technologies	Key economic results	Environmental results	Payback period
Ukraine	MHP	Biogas facilities; renewable energy integration	-25 % energy consumption; -20 % waste-disposal costs; +12 % profitability	≈ 45 000 t CO_2 emissions avoided yr^{-1}; 65 % internal energy self-sufficiency	3.8 yrs
	Molokiya	Smart process control; energy-efficient pasteurization; closed-loop water system	-17 % electricity use; -15 % production losses; -13 % operating costs	−22 % water use; +18 % shorter production cycle	4 yrs
Azerbaijan	Azersun Holding	Solar-panel system (8.5 MW); AI-based waste sorting	-35 % electricity cost; +14 % profitability	−70 % landfilled waste; 92 % recycling efficiency	3 yrs
Bulgaria	Bella Bulgaria	Predictive analytics; AI-driven maintenance; digital energy monitoring	-18 % energy use; -12 % raw-material waste; -28 % downtime	Improved resource utilization + enhanced process stability	2.5 yrs
	Nestlé Bulgaria	Renewable energy integration; packaging recovery	-30 % waste-management cost; -40 % carbon emissions	97 % material reuse; 20 % on-site energy generation	3 yrs
Kyrgyzstan	Bishkeksut	Automated quality & waste monitoring	-12 % energy use; -9 % raw-material loss	Improved quality consistency	5 yrs
	Kant Sut	Organic waste-to-biogas system	15 % of plant energy covered by biogas	−10 % waste volume	4.5 yrs

Explanatory notes / Objaśnienia: compiled by the authors / zebrane przez autorów.

Climatic and natural conditions also have a significant impact, especially in terms of water management and the use of renewable energy sources. For example, solar energy has high potential in Azerbaijan and Ukraine. In Ukraine, in addition to solar energy, biogas and wind energy are actively developing, which opens opportunities to reduce the carbon footprint of food processing companies.

Social and human resources aspects are substantial, as the successful implementation of technologies requires training and changes in corporate culture. The development of educational programs, staff training and the involvement of experts contribute to the effective use of new solutions [67]. In Ukraine, the demand for sustainability specialists has been growing, and the country's leading universities are developing training programs for the environmentally friendly economy. Infrastructure and logistics are also crucial to the success of the transition to sustainable production. The availability of efficient transport routes, processing plants and affordable supply channels for environmentally friendly materials accelerates the implementation process and makes it more cost-effective. In Ukraine, the development of recycling infrastructure is a priority area within the national strategy for sustainable development [13, 10].

In Bulgaria, the success of sustainable technologies is largely determined by its membership in the EU, which provides the country with access to EU structural funds, technical assistance and mandatory regulatory standards for environmental modernization. Government strategies for digitalization and transition to a green economy are significant, as reflected in the food industry. Bulgarian enterprises receive support in the form of subsidies, tax breaks and consulting support for the implementation of energy-efficient solutions and digital platforms. In addition, a well-developed training system and technological competence centers facilitate rapid innovation and strengthen the sustainable manufacturing sector. Efficient logistics, a high level of automation and integration with pan-European supply chains also accelerate the adoption of sustainable practices.

In Kyrgyzstan, by contrast, the introduction of sustainable technologies faces a number of institutional and resource constraints. One of the key challenges is the low level of technical equipment of food processing enterprises, especially in rural areas. There is also a lack of qualified personnel and affordable financing mechanisms, especially for small and medium-sized businesses. Nevertheless, international projects are being implemented in the country with the support of organizations such as the United Nations Development Program, the Food and Agriculture Organization and other donors aimed to introduce basic sustainable production technologies. In particular, initiatives are being developed to promote energy efficiency, waste recycling and the use of solar energy in remote regions. Kyrgyzstan's climatic conditions can be used in the development of solar and hydro resources, which opens the potential for expanding the use of renewable energy sources. Overall, sustainable development in the Kyrgyz food industry relies on a combination of international support, the adaptation of low-cost solutions and the gradual modernization of infrastructure.

Table 4 shows data on production cost reductions at various companies using environmentally sustainable technologies.

The data analysis shows that the largest reduction in production costs (20 ÷ 25 %) is achieved by introducing biogas plants and renewable energy sources. This high figure is determined by several factors: a significant reduction in the cost of traditional energy sources, the possibility of generating additional income from the sale of surplus energy and government programs to support green energy. The digitalization of processes demonstrates the second-highest cost reduction rate (15 ÷ 18 %), which is due to the optimization of production processes, reduction of equipment downtime and minimization of the human factor.

Table 4. Reduction of production costs by implementing sustainable technologies.
Tabela 4. Obniżenie kosztów produkcji poprzez wdrożenie zrównoważonych technologii.

Enterprise category	Average cost reduction [%]
Energy-saving technologies	12-18
Waste management	10-14
Digitalization of processes	15-18
Use of biogas and renewable energy sources	20-25

Explanatory notes / Objaśnienia: compiled by the authors / zebrane przez autorów.

Automation and the introduction of predictive analytics systems can significantly reduce operating costs and production losses. Energy-saving technologies reduce costs by 12 ÷ 18 %. This range of savings is explained by differences in the initial level of energy efficiency of enterprises and the types of solutions implemented. The greatest effect is achieved through the comprehensive modernization of production equipment and the implementation of energy management systems.

Climate change has become a critical determinant of the global food industry's stability and profitability. Rising temperatures, irregular precipitation and the increasing frequency of extreme weather events directly affect agricultural productivity and the availability of raw materials used in food production. Studies indicate that a 1 °C increase in average global temperature may reduce yields of key crops such as wheat, maize and soybeans by 6 ÷ 10 %, thereby raising the cost of raw materials and destabilizing supply chains. This, in turn, increases production expenses and the volatility of food prices.

Additionally, higher temperatures accelerate spoilage and reduce the shelf life of perishable goods, requiring the industry to invest in more advanced refrigeration, packaging and logistics systems to maintain quality and safety standards. In regions such as Central Asia and Eastern Europe, including Ukraine, Bulgaria and Kyrgyzstan, climate variability has already caused seasonal shortages of raw materials, underscoring the need for adaptive production planning and diversification of suppliers.

At the same time, the food industry is one of the major contributors to greenhouse gas emissions, accounting for approximately 26 % of total global emissions, primarily through agricultural processes, energy consumption and waste management. Thus, the sector faces a dual challenge: mitigating its environmental impact, while adapting to the consequences of climate change. The integration of climate-resilient technologies, such as precision irrigation, renewable energy use and bio-based packaging, offers potential economic and ecological benefits. For instance, the implementation of energy-efficient systems and renewable energy sources in food processing plants can reduce CO_2 emissions by up to 40 % and energy costs by 25 ÷ 30% over the long term. Consequently, climate adaptation strategies are increasingly becoming not only an ecological imperative, but also a crucial component of sustainable competitiveness in the global food industry.

The use of sustainable production technology in the examined firms has yielded significant socio-environmental advantages, notably in employment generation and the decrease of greenhouse gas emissions. The examined projects collectively generated nearly 2,400 new jobs in the food industry across the four participating nations, primarily in renewable-energy management, process automation, environmental monitoring and circular-economy logistics. Ukraine and Bulgaria contributed to over 70 % of the overall job growth, indicative of their advanced digital and technological sophistication. Furthermore, the shift towards energy-efficient and waste-to-biogas technologies facilitated the creation of ancillary sectors (maintenance services, recycling subcontractors and logistics providers), hence broadening regional employment markets and fostering specialist vocational training.

The total reduction of CO_2 emissions surpassed 120,000 tonnes annually, primarily attributed to MHP's biogas facilities (approximately 45,000 t CO_2 yr^{-1}), Azersun Holding's solar initiative (approximately 28,000 t CO_2 yr^{-1}), and Nestlé Bulgaria's packaging-recovery system (approximately 22,000 t CO_2 yr^{-1}). These accomplishments correspond with the UN Sustainable Development Goals (SDGs 7, 9, and 13), illustrating that sustainable industrial modernization may concurrently foster economic resilience and decarbonization. The results affirm that the transition to renewable energy, digital process management and circular resource utilization not only diminishes production expenses, but also generates enduring environmental and social benefits that bolster the competitiveness and sustainability of national food sectors.

Waste management shows the lowest, but stable cost reduction (10 ÷ 14 %). The lower figure is due to the need for significant initial investment in recycling infrastructure and a longer payback period. However, this area has a significant potential for efficiency growth with the development of recycling technologies and the expansion of secondary raw material markets. In the context of global market changes, the analysis of long-term trends in the introduction of sustainable technologies is of particular importance. The study demonstrated that companies investing in environmentally friendly technologies demonstrate greater resilience to market fluctuations and are better able to adapt to changes in the regulatory environment. This is particularly noticeable in times of economic instability, when resource efficiency becomes a critical factor in the survival of enterprises.

The findings closely correspond with the aims of global sustainability frameworks, including the European Green Deal and the United Nations Sustainable Development Goals (SDGs), specifically SDGs 7 (Affordable and Clean Energy), 9 (Industry, Innovation and Infrastructure), and 12 (Responsible Consumption and Production). In alignment with the Green Deal's focus on decarbonization, energy efficiency and circular economy concepts, the examined firms realized substantial decreases in energy consumption and waste production via the incorporation of renewable energy and resource recovery systems. The documented profitability increases of $8 \div 15\ \%$ from circular production models align with the UN's objective of sustainable industrial transformation that harmonizes economic growth with ecological integrity. Furthermore, the study's evidence of emission reductions beyond 120,000 t CO_2 per year signifies tangible advancement towards the EU's climate neutrality objective for 2050. Nevertheless, in relation to these global norms, obstacles remain in reconciling developing economies, such as Azerbaijan and Kyrgyzstan, with the administrative and financial frameworks necessary for the extensive implementation and oversight of environmental innovations.

An analysis of the international experience of implementing sustainable technologies shows significant differences in approaches and results between different regions. European companies, for instance, demonstrate a higher level of integration of environmental technologies, which is largely due to strict regulatory requirements and a developed system of government support. Asian manufacturers, in turn, focus on optimizing production processes and introducing energy-saving technologies [8].

A substantial aspect identified in the course of the survey is the social effect of the introduction of sustainable technologies. Businesses report an increase in the level of staff engagement, growth of professional competencies and the formation of a new corporate culture focused on sustainable development. In addition, the improvement of environmental performance has a positive impact on the reputation of companies and their relations with local communities.

Investment aspects analysis of the investment attractiveness of sustainable technology projects shows that the average payback period for such investments is three to five years, making them attractive to long-term investors. At the same time, there is a tendency for payback periods to be shorter due to the development of technologies and the growth of the efficiency of solutions. This is especially true for energy efficiency and waste management projects.

Technology trends and strategic recommendations

The study identified key technological trends that will shape the development of sustainable production in the coming years. The development of artificial intelligence technologies to optimize production processes is of paramount importance, as it can significantly improve the efficiency of operations. At the same time, the introduction of closed production cycles is actively developing to ensure maximum resource utilization. Of particular relevance is the development of energy storage and energy recovery technologies to optimize energy consumption. The integration of the industrial Internet of Things (IoT) is becoming a prerequisite for creating smart manufacturing, while the development of biotechnology for waste treatment opens new opportunities for improving environmental sustainability.

Despite the advantages, the introduction of sustainable technologies faces a number of significant barriers. High initial investment costs are often the main obstacle to modernizing production. The lack of qualified personnel makes it difficult to use new technologies effectively. Integration of innovations into existing production processes poses significant challenges. Uncertainty in the regulatory environment and limited access to finance for small and medium-sized enterprises also slow down the process of adopting sustainable technologies. The examination of particular obstacles to the implementation of sustainable technologies disclosed notable disparities among the studied nations, indicative of differences in institutional ability, economic framework and technological advancement.

The primary challenge in Ukraine is the restricted availability of long-term finance for industrial modernization. Large firms like MHP and Molokiya capitalize on international investment and EU-aligned grant channels, whereas small and medium-sized food producers face challenges in securing credit for environmental enhancements due to elevated interest rates and inadequate state guarantees. A continual obstacle is regulatory inconsistency: periodic modifications to environmental legislation and delays in aligning national standards with EU regulations generate uncertainty for investors. Moreover, infrastructural limitations, such as antiquated logistical networks and inadequate waste recycling capabilities in rural regions, hinder the comprehensive adoption of circular-economy techniques.

The primary challenges in Azerbaijan pertain to institutional and technological preparedness. Despite governmental endorsement of green measures via strategic programs, the industrial sector continues to be significantly energy-intensive and dependent on fossil fuels. The initial capital expenditures for renewable installations and advanced manufacturing systems are excessively exorbitant for numerous firms outside major conglomerates like Azersun Holding. The deficiency of technical specialists proficient in sustainable production, automation and environmental management obstructs the dissemination of innovative technology. The restricted local production of green equipment exacerbates reliance on imports, inflating costs and prolonging project execution timeframes.

In Bulgaria, there are relatively fewer obstacles, yet they are still significant. The nation's European Union membership guarantees access to structural funding and a solid regulatory framework; yet, businesses encounter administrative complexities in securing subsidies and meeting reporting obligations. The disintegration of support programs among ministries frequently postpones project clearance, while substantial compliance expenses linked to EU environmental audits discourage smaller enterprises. Notwithstanding a robust digital infrastructure, regional inequalities endure - rural food-processing facilities, specifically, face delayed implementation of digital solutions owing to inferior broadband access and worker relocation to urban centres.

The obstacles in Kyrgyzstan are mostly structural and resource-oriented. The food business utilizes outdated equipment and exhibits insufficient automation, while companies possess restricted abilities to invest in sustainability. Financial limitations are significant: local banks infrequently provide green loans and international funders support only a minor portion of businesses. The absence of regulatory enforcement mechanisms results in inadequate adherence to environmental standards. Rural firms frequently encounter difficulties in accessing reliable electricity and skilled technicians, rendering the installation of energy-efficient or renewable systems technically arduous. Cultural considerations influence the situation; numerous local producers are suspicious about environmental technologies, viewing them as expensive and unproven.

These findings emphasize that although the primary barriers, such as investment, knowledge and regulatory uncertainty – are prevalent, their strength and configuration vary significantly among countries. Overcoming these challenges necessitates tailored policy interventions: improved credit instruments and clearer regulatory frameworks in Ukraine; technology transfer and workforce development in Azerbaijan; administrative simplification and rural digital infrastructure in Bulgaria; and robust financial and institutional support systems in Kyrgyzstan. These diversified initiatives would facilitate the transition of sustainable technology from isolated pilot projects to comprehensive industrial transformation throughout the area.

Based on the analysis, key strategic recommendations for enterprises were formulated. The priority is to develop a long-term sustainable development strategy with clear quantitative indicators. A substantial element is the creation of an effective environmental risk management system. The development of staff competencies in sustainable technologies is also substantial. It is necessary to create a comprehensive system for monitoring and evaluating the effectiveness of the solutions implemented. The development of partnerships with scientific organizations and technology companies is essential.

In the context of the results obtained, the priority areas for further research were identified. An in-depth study of the impact of sustainable technologies on the competitiveness of enterprises in various industries is needed. Analyzing the effectiveness of different models of financing environmental projects remains relevant. It is necessary to conduct a comprehensive study of the social effects of the introduction of sustainable technologies. It is necessary to develop a methodology for assessing the long-term effects of environmental innovations. Of particular importance is the study of mechanisms for the transfer of sustainable technologies between developed and developing countries.

This study confirmed that the introduction of sustainable technologies is not only an environmental necessity, but also a substantial factor in increasing the competitiveness of enterprises. In the context of growing attention to climate issues and stricter environmental requirements, the ability of enterprises to effectively implement sustainable technologies is becoming a key factor in their long-term success.

A coordinated strategy for the three sectors should integrate enterprise-level implementation with supportive policies and applied research: enterprises will conduct a 12-month baseline audit (energy, water, waste) and undertake measures with rapid returns on investment (automated energy consumption monitoring, intelligent process control, preventive maintenance), while progressively adopting circular economy practices (waste conversion to biogas, packaging recycling) and establishing verifiable key performance indicators (KPIs) for costs, emissions and material reuse within 24–36 months; governments will create stable long-term incentives (accelerated depreciation, tax incentives, green certificates/guarantees of origin), mitigate financing risks through preferential green credit lines and loan guarantees for SMEs, mandate reporting standards, enhance waste processing/logistics infrastructure and finance workforce retraining in digital technologies and sustainable development.

The scientific community establishes industry test beds and living laboratories in prioritized sub-sectors (e.g. bakery and dairy products), offers open life cycle assessment (LCA) and techno-economic analysis (TEA) toolkits along with benchmark datasets, collaboratively develops low-capital-cost retrofits tailored to local constraints and performs continuous evaluations to quantify returns (e.g. 12 ÷ 18 % reduction in energy costs via smart monitoring, 8 ÷ 15 % enhancement in profitability through circular models and 30 ÷ 40 % long-term savings through renewable energy sources), while a joint public-private steering committee publishes annual progress reports and modifies the policy and technology framework based on empirical findings.

The study's findings may be influenced by several potential biases, primarily stemming from the subjectivity of expert assessments and the limited representativeness of the sample. Expert evaluations, while valuable for contextual insights, may reflect individual perceptions shaped by a professional background or institutional affiliation, leading to potential overestimation of certain technologies' effectiveness. Additionally, the empirical data are largely derived from large, well-documented enterprises, with small and medium-sized enterprises (SMEs) underrepresented due to limited reporting and data accessibility. This imbalance may constrain the generalizability of conclusions, particularly regarding the financial and operational feasibility of sustainable technologies in less resourced or rural production contexts.

Discussion

The empirical results of the study showed that the introduction of sustainable technologies in the food industry has a significant positive impact on the economic efficiency of enterprises. The study confirmed that the use of energy-saving technologies, digitalization, waste recycling and renewable energy sources can reduce operating costs, increase profitability and improve environmental sustainability.

Circular economy and resource management. The transition to the principles of the circular economy has reduced the cost of purchasing raw materials by 10 ÷ 14 %. This result correlates with the findings of Ahmed et al. [1], demonstrating that the reuse of materials and waste significantly increases the operational efficiency of enterprises and reduces their environmental impact. The results confirm the hypothesis of Wang et al. [71], according to which environmental innovations not only reduce negative environmental impacts, but also help to reduce costs. In particular, waste recycling creates additional sources of income from the sale of secondary raw materials. Similar conclusions are presented in the study by Kucher et al. [42], noting that waste recycling can increase the profitability of enterprises by 5 ÷ 10 %.

International experience shows that companies investing in sustainable technologies are more resilient to market fluctuations. In the EU, strict environmental regulations have contributed to the widespread adoption of energy-saving technologies and circular production models [14]. In Asia, priority is given to the digitalization of production processes. According to Paiva et al. [51], the use of IoT and predictive analytics can reduce production costs by 10 ÷ 15 %. Although this aspect was not directly analyzed in this study, international experience confirms that the digitalization of resource and waste management can significantly improve operational efficiency and reduce environmental impact.

The results of this study, which show a 30 ÷ 40 % reduction in electricity costs with the introduction of renewable energy sources, correlate with international research in this area. This coincidence can be explained by several factors. Firstly, solar and wind energy technologies have improved significantly, as evidenced by the research of Bajan et al. [4] demonstrating a 25 % increase in the efficiency of photovoltaic systems. Secondly, the reduction in the cost of renewable energy equipment noted by Veloso et al. [70] makes such investments more affordable and economically attractive for food processing companies.

However, the results of the study demonstrate a higher percentage of savings compared to the studies by Hoang-Khac et al. [28] and Hegab et al. [27], where the average figure was 25 ÷ 35 %. This discrepancy may be due to the peculiarities of the climatic conditions of the studied regions and differences in government programs to support renewable energy. In addition, the higher efficiency rates in this study may be due to an integrated approach to the implementation of energy-saving technologies, including the simultaneous use of energy storage systems and intelligent energy management.

The problem of climate stress is also presented in detail in the study by Zhang et al. [73], noting an increase in the frequency of extreme temperature conditions in key grain regions of the world. These data overlap with the observations of this study, especially in terms of the need to adapt production strategies to climate challenges. However, in this case, the emphasis is on the practical implementation of energy-saving measures and sustainable technologies, not just on agronomic adaptations such as heat-tolerant varieties.

A study by Li et al. [44] on the use of biochar for soil restoration and climate change adaptation is noteworthy. While their approach focuses primarily on agro-ecological aspects, this study complements their findings from the economic side, confirming that environmentally friendly technologies can simultaneously ensure business profitability and sustainability. A systemic approach to the relationship between climate and food systems is demonstrated by Niles et al. [50], emphasizing the vulnerability of supply chains and the importance of adaptation mechanisms in supply management. In the context of the present study, this confirms the importance of integrating sustainable solutions not only at the production level, but also in related elements of the value chain. In turn, Runhaar [56] raises the issue of institutional transformation required for a sustainable transition. In contrast to the focus of this study on technological and operational aspects, they emphasize the need to revise governance mechanisms and interactions between sectors.

The study by Pretty et al. [52] complemented the picture by focusing on sustainable intensification as a means of increasing productivity without increasing the ecological footprint. The observations in this study on the combination of economic and environmental benefits when introducing circular and energy-saving technologies correlate well with this position. Searchinger et al. [58] and Foley et al. [19] emphasized the need for a comprehensive approach to food system transformation, including dietary changes, minimizing losses and innovative natural resource management. The data obtained in this study on cost reductions and increased sustainability of enterprises confirm the effectiveness of such approaches at the micro level.

The introduction of sustainable technologies in the food industry brings measurable economic and environmental benefits. Energy-efficient solutions, digitalization, waste recycling and the use of renewable energy sources help to reduce costs, improve operational efficiency and increase the resilience of enterprises to external fluctuations [5; 29]. International experience confirms the universality of these approaches, although the effectiveness of their implementation depends on the specifics of each country in terms of infrastructure, regulatory environment and investment support. The data obtained indicate the need for a comprehensive and systematic approach to the implementation of sustainable practices, which forms the basis for further conclusions and strategic recommendations.

Subsequent research should concentrate on micro-level dynamics, namely small and medium-sized food firms that were omitted from the current analysis, to comprehend scalability and local innovation impediments. Furthermore, the quantitative assessment of digital technologies, such as IoT, AI-driven analytics and predictive maintenance, necessitates advanced econometric modelling to ascertain their precise impacts on cost savings and environmental performance. The socio-economic aspects of sustainable transformation, such as workforce adaptation, gendered involvement in green employment and community effects of circular practices, are still examined to a lesser extent. Ultimately, sustainable projects in developing economies necessitate a thorough examination of long-term financial systems and risk-adjusted investment models to guarantee fair and lasting execution.

Conclusions

1. The study confirmed that the introduction of sustainable technologies in the food industry of Azerbaijan, Ukraine, Kyrgyzstan and Bulgaria helps to increase economic efficiency, reduce operating costs and improve the environmental sustainability of enterprises. The study identified key areas of sustainable development, including energy efficiency, digitalization, waste management and the use of renewable energy sources.
2. The survey results demonstrated that the use of intelligent energy management systems reduced energy costs by 12 ÷ 18 %. Optimizing resource consumption and switching to circular production models can increase profitability by 8-15 %, while the use of renewable energy sources reduces dependence on traditional energy resources in the long term and cuts costs by 30 ÷ 40 %. The introduction of waste management technologies, including the production of biogas and recycled materials, not only reduces waste, but also generates additional revenue.
3. The introduction of sustainable technologies in the bakery industry is a particularly promising area. Given the high energy consumption of bakeries, the use of renewable energy and energy-efficient equipment can significantly reduce costs. For instance, the use of innovative heat recovery ovens reduces energy consumption by 15 ÷ 25 %. In addition, the automation of fermentation and baking processes using digital technology helps to improve product quality and reduce production losses.
4. The digitalization of production processes is considered to be one of the most promising areas for improving operational efficiency in the food industry. Although this area has not been quantitatively analyzed in this study, literature and international experience indicate that the use of IoT, machine learning and predictive analytics can help reduce costs, minimize production losses and increase the trans-

parency of supply chains. In particular, in Bulgaria, digital technologies are being actively integrated into production and energy management, while in Kyrgyzstan, the first initiatives to automate quality control and waste monitoring are being formed. These aspects require further empirical study in the context of the food industry in Azerbaijan, Ukraine, Bulgaria and Kyrgyzstan.

5. However, barriers to the adoption of sustainable technologies have also been identified, including high initial investment costs, a shortage of qualified specialists and the difficulty of integrating new solutions into existing production processes. To overcome these barriers, it is necessary to develop financial support mechanisms, encourage small and medium-sized businesses and introduce educational programs to train specialists in sustainable production.
6. Thus, ensuring the sustainable development of the food industry, including bakery production, requires a comprehensive approach that includes technological, economic and social aspects. The introduction of innovative solutions helps to improve the efficiency of enterprises, minimize environmental impact and strengthen their positions in the international market. The results confirm the economic feasibility of using sustainable technologies and emphasize their importance for improving resource efficiency and reducing production costs.
7. At the same time, the study has certain limitations. Firstly, it covers only four countries and focuses on large enterprises, while small and medium-sized businesses were omitted from the study. It also did not conduct a detailed quantitative analysis of the impact of digital solutions such as IoT or machine learning, which limits the completeness of the assessment of their contribution to the sustainability of production processes. In addition, some of the data was based on open sources, which could affect the accuracy of certain indicators. Promising areas for further research include analyzing the impact of sustainable technologies on the competitiveness of enterprises in various industries, developing financial instruments to support environmentally friendly solutions, studying the social effects of automation and digitalization, and assessing the long-term economic impact of sustainable innovations.

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OCENA WPŁYWU ZRÓWNOWAŻONYCH METOD PRODUKCJI NA EFEKTYWNOŚĆ EKONOMICZNĄ W PRZEMYŚLE SPOŻYWCZYM

S t r e s z c z e n i e

Wprowadzenie. Celem badania była analiza wpływu zrównoważonych metod produkcji na efektywność ekonomiczną przedsiębiorstw przemysłu spożywczego. W badaniu przeanalizowano aktualne trendy we wdrażaniu technologii energooszczędnych, cyfryzacji, gospodarce odpadami i zasadach gospodarki o obiegu zamkniętym, a także przeanalizowano korzyści ekonomiczne wynikające z zastosowania inteligentnych systemów sterowania i odnawialnych źródeł energii. Zautomatyzowane systemy monitorowania zużycia energii obniżyły koszty energii o 12 ÷ 18 %, a integracja odnawialnych źródeł energii obniżyła koszty o 30 ÷ 40 % w perspektywie długoterminowej.

Wyniki i wnioski. Badanie wykazało, że przejście na modele produkcji o obiegu zamkniętym zwiększa rentowność o 8 ÷ 15% poprzez redukcję kosztów zakupu surowców i optymalizację przetwarzania odpadów. Badanie wykazało, że przedsiębiorstwa wdrażające zaawansowane technologie przetwarzania odpadów mogą nie tylko zminimalizować koszty ich utylizacji, ale także stworzyć nowe źródła dochodu poprzez produkcję biogazu, dodatków paszowych i materiałów wtórnych. Badanie dowiodło, że wykorzystanie inteligentnych czujników i algorytmów uczenia maszynowego może zoptymalizować zużycie zasobów, zapobiegać awariom sprzętu i redukować straty produkcyjne. Technologie te pomagają również zautomatyzować procesy kontroli jakości oraz zapewnić dokładniejsze prognozowanie popytu i zarządzanie zapasami. Zidentyfikowano kluczowe bariery utrudniające wdrażanie zrównoważonych technologii, w tym wysokie koszty inwestycji, konieczność modernizacji infrastruktury, trudności w integracji z istniejącymi procesami produkcyjnymi oraz brak wykwalifikowanych specjalistów. W badaniu zauważono, że skuteczna realizacja strategii zrównoważonej produkcji wymaga interakcji między biznesem, państwem i środowiskiem naukowym. Rozwój instrumentów finansowych, takich jak ulgi podatkowe, subwencje i programy wspierania innowacji, może znacząco przyspieszyć transformację przedsiębiorstw na przyjazne dla środowiska i opłacalne modele operacyjne. W badaniu stwierdzono, że przedsiębiorstwa inwestujące w innowacyjne metody zrównoważonej produkcji zyskują znaczącą przewagę konkurencyjną i zapewniają długoterminowy wzrost działalności w kontekście globalnej agendy środowiskowej.

Key words: digitalizacja produkcji, efektywność energetyczna, gospodarka odpadami, technologie obiegu zamkniętego, innowacje środowiskowe