Krzysztof **WÓJCICKI** • Michał **MŁODY** • Maja **SAJDAK**

OPPORTUNITIES AND BARRIERS IN THE DIGITAL TRANSFORMATION OF DAIRY INDUSTRY AND ITS IMPACT ON SUSTAINABLE PRODUCTION MANAGEMENT

Krzysztof WÓJCICKI (ORCID: 0000-0003-4902-8613) – Poznań University of Economics and Business, Institute of Quality Science

Michał MŁODY (ORCID: 0000-0001-5368-9719) – Poznań University of Economics and Business, Institute of Management

Maja SAJDAK (ORCID: 0000- 0003-0638-0609) – Poznań University of Economics and Business, Institute of Management

Correspondence address:
Niepodległości Avenue 10, 61-875 Poznań, Poland
e-mail: krzysztof.wojcicki@ue.poznan.pl

ABSTRACT: Purpose: This study investigates the adoption of Industry 4.0 technologies in the Polish dairy industry and their impact on sustainable production management, addressing opportunities, barriers, and strategic implications. Methodology/Approach: A structured CATI survey was conducted with 68 dairy companies. Quantitative data were analysed using descriptive statistics to evaluate disparities in technology adoption and its impact on sustainability outcomes. Findings: Large companies exhibit higher levels of digitalisation, benefiting from increased efficiency, sustainability, and ecological performance. Small and SMEs face barriers such as high costs, limited infrastructure, and workforce challenges. Research limitations/implications: The study's focus on the Polish dairy sector limits generalizability. Future research should explore specific technologies, such as blockchain and AI, and expand to other sectors for broader insights. Practical implications: The findings emphasise the need for financial support, training programs, and tailored strategies to overcome barriers, particularly for SMEs. Originality/Value: Our research bridges the gap between digital transformation and sustainability in the dairy sector, offering actionable insights for managers and policymakers.

KEYWORDS: digital transformation, Industry 4.0, dairy, sustainability

Introduction

The food industry in Poland represents one of the largest and fastest-growing sectors. In terms of milk production, Poland ranks fifh among EU countries (Ziętara et al., 2024). Data from the Ministry of Finance shows that in 2022, the export value of Polish dairy products reached a record EUR 3.6 billion, reflecting a 37% increase compared to 2021. As a result, the dairy sector is regarded as a vital part of the food products market, with significant growth potential and a key contributor to Poland's agricultural GDP. The development of the dairy industry in the era of the digital economy is not possible without the introduction and application of innovative technological solutions, which determine the overall level of competitiveness of the sector (Krajewski, 2023). In general, the adoption of Industry 4.0 technologies in Polish companies is rather slow (when compared to highly developed economies) due to several hurdles to their implementation, which are confirmed by (Młody et al., 2023)

In scientific literature, there has been a systematic increase in interest in issues related to the digital transformation of industry and the implementation of Industry 4.0 technologies. Digital transformation and Industry 4.0 are often used interchangeably (Argilovski et al., 2023). To understand the relationship between these concepts, we used definitions based on Argilovski et al. (Argilovski et al., 2023) – "*Digitalization is defined as the activity of making processes more automated by means of digital technologies (the ones that are part of the I4.0 concept). […] digitalization is the process that precede digital transformation activities to create new business values. Industry 4.0 technologies, which is a set of digital technologies, come as an aid to the organizations to reach digitalization that will lead to the overall digital transformation of the organization*".

The research area related to Industry 4.0 is analysed both from a technical perspective and in the context of sustainable development (Varriale et al., 2024) independently. While numerous articles address the opportunities and challenges of digital transformation, there is a noticeable gap in studies that integrate these aspects with the barriers related to sustainable management. This gap reveals the need for comprehensive research that examines how companies navigate the interplay between digital transformation and sustainable management, offering a holistic perspective on addressing these interconnected issues.

Thus, this article aims to fill this gap by examining how companies manage the opportunities and barriers of digital transformation while meeting the demands of sustainable management. Our study seeks to provide practical insights into balancing these two important areas.

Our study is important because of the EU's adoption of the Green Deal (Ejdys & Szpilko, 2022), Farm-to-Table, Biodiversity, and other sustainability (non-financial reporting – ESG) requirements, as well as packaging management regulations (both at EU and national levels), which means big changes in agriculture, food production, and consumption (Matuszak-Flejszman et al., 2024). To meet these demands, the dairy industry needs to modernise its existing production, including through the implementation of digital technologies (Feil et al., 2023; Matuszak-Flejszman et al., 2024). We investigate how Polish companies prepare to meet these demands.

The article comprises key sections: an introduction highlighting the importance of digital transformation and sustainability in the dairy industry, a literature review on Industry 4.0 technologies and research gaps, and a methodology detailing CATI surveys and analysis. Results reveal technology adoption levels and impacts on sustainable production by company size. The discussion connects findings to the literature, noting limitations and future research. The conclusion outlines practical implications and scientific contributions.

An overview of the literature

In recent years, the world has faced the great issue of digital transformation. If we track interest in digital transformation among firms, we see a rapid increase starting in 2014–2015 (Kim et al., 2021). Industry 4.0 represents the digital transformation of manufacturing systems, moving from "machine manufacturing" to "digital manufacturing," driven primarily by information technology (Oztemel & Gursev, 2020). According to Hassoun et al. (2023), the principal objective of Industry 4.0 technologies is to reduce production costs while simultaneously enhancing flexibility and agility

DOI: 10.34659/eis.2025.94.3.1081

through the implementation of enhanced production and quality improvement. According to Zheng (2021), the transformation to Industry 4.0 is driven by the demand for faster delivery, more effective and automated processes, better quality and customised products. Młody et al. (2023) demonstrate that Industry 4.0 technologies had a positive impact on the quality and speed of the managers' decision-making process across the different stages of the value chain.

The main technologies of Industry 4.0 are Artificial Intelligence (AI), Internet of Things (IoT), robotics, smart sensors, Big Data, blockchain, radio frequency identification (RFID), virtual reality (VR), the cloud, 3D printing, cyber-physical systems (CPS), digital twins, cyber security, automation and machine learning (ML) (Hassoun, Garcia-Garcia, et al., 2023; Wichmann et al., 2019; Wójcicki et al., 2022). The application of these technologies in agriculture is often referred to as smart farming, precision agriculture, or Agriculture 4.0 (Javaid et al., 2022; Sinha & Dhanalakshmi, 2022). Similarly, food factories that use these advanced technologies are often called "smart factories" (Mavani et al., 2022).

The contemporary food industry is a highly competitive and rapidly evolving sector, characterised by an increasing consumer demand for superior quality, safety, and durability of food products, coupled with a growing preference for greater product variety and sustainable production methods (Wójcicki et al., 2024). A growing scientific literature demonstrates that the implementation of technologies associated with the fourth industrial revolution has revolutionised how food is produced, transported, stored, perceived, and consumed worldwide, leading to the emergence of new food trends (Hassoun, Aït-Kaddour, et al., 2022; Hassoun, Bekhit, et al., 2022). According to Wójcicki et al. (2024), food producers can use technological approaches to solve problems such as food safety and quality, production optimisation, traceability, shelf-life control, and other related issues in the context of food production. The integration of digital technologies in the food supply chain supports sustainable development in the agri-food sector. The general overview of key Industry 4.0 principles and their application in food production was presented by Hassoun et al. (2022) and Wójcicki et al. (2024).

The dairy industry plays a crucial role in the global food system, providing a wide range of dairy products that are consumed by millions of people worldwide (Fiorillo & Amico, 2024). The significance of dairy products in a well-balanced diet for human health is attributable to their nutritional value, particularly their content of proteins, lipids, mineral components, and vitamins (Barłowska et al., 2011). The dairy industry remains at the leading edge of technological change, with new technologies and technical innovations emerging in all areas of the sector (Malik et al., 2024). It has come a long way from traditional farming methods and manual milk processing. Today, technological advancements and digitalisation are transforming the dairy sector, improving efficiency, quality, and sustainability (Hassoun, Garcia-Garcia, et al., 2023). The application of Industry 4.0 technologies in the dairy sector is termed "Dairy 4.0 " (Hassoun, Garcia-Garcia, et al., 2023; Konstantinidis et al., 2023). For example, IoT sensors can monitor milk quality and animal health in real-time, while AI algorithms optimise feeding and milking schedules to improve yield and reduce waste. These innovations enhance operational efficiency while supporting sustainable production practices by minimising resource use and environmental impact (Tangorra et al., 2024). The implementation of blockchain technology in the milk supply chain guarantees the traceability of products throughout the supply chain, from the farm to the consumer. This transparency fosters trust, enables compliance with sustainability standards, and empowers consumers to make informed decisions regarding the products they purchase (Vp et al., 2022). Furthermore, AI optimises feed composition and energy management, integrating renewable energy sources such as solar or biogas into operations, thereby reducing reliance on fossil fuels in the dairy industry (Neethirajan, 2024). In the dairy sector, ML is being used to monitor every stage of the milk production cycle in order to lower the possibility of negative farm events that could have an impact on productivity and profitability (Samson et al., 2023). The integration of Industry 4.0 technologies across various sectors, including the dairy industry, has revolutionised traditional practices. Thus, it could position "Dairy 4.0" as a transformative approach to modernising the global food system.

DOI: 10.34659/eis.2025.94.3.1081

Research Methodology

Method

The research design for this study follows a structured approach to address the opportunities and barriers of digital transformation in the dairy industry, with a focus on sustainable production management. The study was conducted in 2024 and has been divided into two major parts: conceptual framework development and data collection and analysis. The research procedure (Figure 1) covered 8 steps. The process begins with a clear definition of the research problem and objectives (step 1), emphasising the integration of Industry 4.0 technologies with sustainability demands. A conceptual framework was developed to link these dimensions, supported by a comprehensive literature review (step 2).

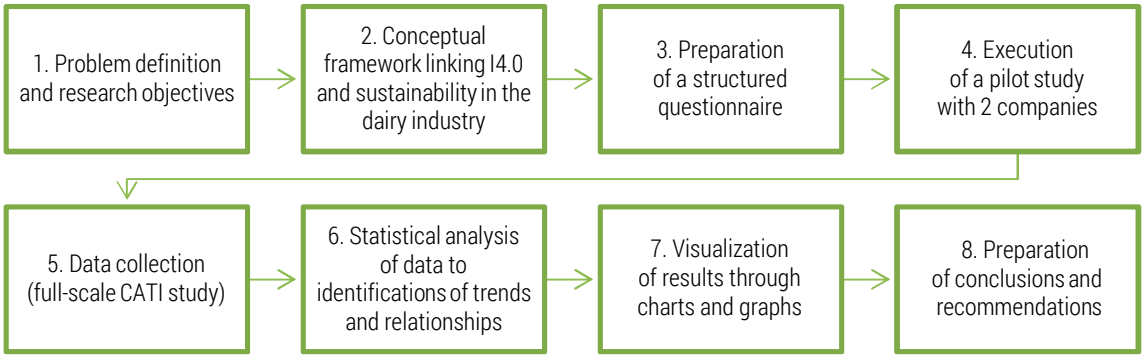

Figure 1. Research design

A structured questionnaire was crafted and tested through a pilot study with two companies to ensure clarity and reliability (steps 3-4). The questionnaire contained 23 questions related to: (1) digital awareness and strategy, (2) digital technologies and processes, (3) digital competencies, (4) data management and cybersecurity, and (5) quality and sustainable production. The 5-point Likert scale was used in the research due to its simplicity, versatility, and ability to measure subjective attitudes or opinions quantitatively. Such a scale allows respondents to express the intensity of their agreement or disagreement with a statement on a graduated scale, typically ranging from "Strongly disagree" to "Strongly agree." Our study was conducted by an external, professional company (step 5). The study employed a Computer-Assisted Telephone Interview (CATI) survey, a method widely used in industrial research to ensure structured, high-quality data collection (Groves & Mathiowetz, 1984). This approach was particularly suitable for the dairy industry, where direct access to decision-makers is often limited. The use of trained interviewers helped reduce response bias and ensured clarity in data interpretation. Given the study's focus on digital transformation, the structured nature of CATI allowed for consistent measurement of technology adoption levels across company sizes. The collected data underwent rigorous statistical analysis to identify trends, assess impacts, and highlight disparities, strengthening the empirical basis of our conclusions (step 6). The results were visualised through detailed graphs and charts (step 7), providing actionable insights into how Industry 4.0 technologies can address sustainability challenges (step 8).

Data collection and data analysis

The study was conducted in February 2024 and involved employees in key decision-making positions, such as company owners, quality directors, production managers, and technologists. Their expertise ensured that responses reflected the strategic and operational realities of digital transformation in the dairy sector. The sample was selected based on available registers of dairy companies in the Polish Classification of Activities (PKD 10.51), according to which 476 dairy processing companies are registered. Responses were obtained from 68 companies, ultimately obtaining a response rate of 13.9% (purposive sampling). While the sample provides valuable insights into digital adoption, its size presents a limitation in terms of broader generalizability. The predominance of SMEs in

DOI: 10.34659/eis.2025.94.3.1081

the dataset (88.5%) reflects industry demographics but may underrepresent the experiences of large enterprises, which often have different investment capacities and strategic approaches to Industry 4.0 adoption. Future research should aim to expand the sample size and include a more diverse range of firms to provide a comprehensive view of digital transformation in the sector. Adopted methodology enabled a detailed evaluation of differences in the adoption of Industry 4.0 technologies and their impact on sustainable production.

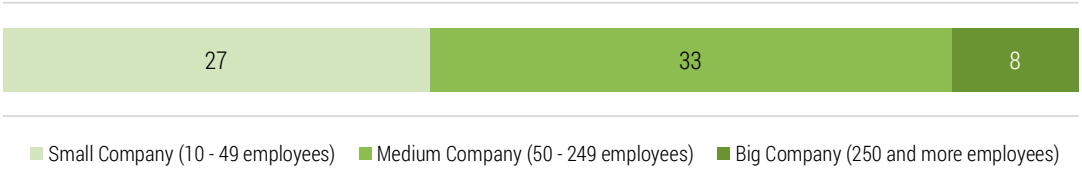

Figure 2. Structure of a sample based on the number of employees

The analysis was conducted using SPSS, a robust statistical software, which enabled the application of descriptive statistics. Our study primarily relied on descriptive statistics to explore differences across small, medium, and large companies. Statistical analysis included the calculation of averages to measure, i.e. the degree of automation and digital technology adoption across different company sizes. While no formal statistical significance tests were conducted at this stage, future analyses will incorporate inferential methods, such as t-tests and ANOVA, to further validate these findings. To enhance the interpretation of results, key trends were visualised using detailed graphs and charts.

Results of the research

Application of digital technologies

A review of the responses to the question about the level of automation in production processes, categorised by company size, reveals notable contrasts between the groups (Figure 3). The provided average response values (from 1 – "fully manual operations" to 4 – "fully automated processes") indicate that there are differing approaches to automation depending on the size of the company. The average score for small companies is 1.59, indicating that manual operations remain the dominant approach. This result indicates that small businesses frequently lack the financial or technological resources to invest in advanced automation. The average response for medium companies is 2.39, indicating a transitional phase from manual operations toward automation. Medium-sized companies appear to have greater capacity to invest in automation technologies, though they have not yet reached the level of large companies.

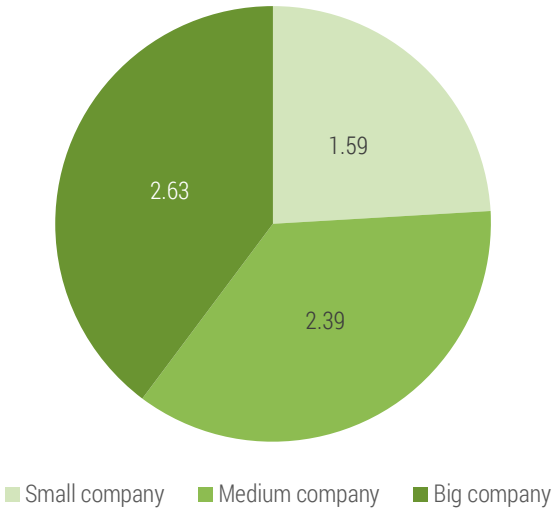

Figure 3. The level of automation of the company's production processes. 1 Fully manual operations, 2 Prevalence of manual operations, 3 Prevalence of automated processes, 4 Fully automated processes (robotization), 0 don't know/don't have an opinion.

In contrast, large companies scored an average of 2.63, indicating a higher level of process automation. This is driven by larger financial resources, economies of scale, and the necessity to remain competitive in the market. A comparison of these results reveals a significant disparity between small companies (1.59) and both medium (2.39) and large companies (2.63). The

DOI: 10.34659/eis.2025.94.3.1081

notable difference between small and medium companies (0.80) may underscore the barriers faced by small companies in adopting automation technologies. Conversely, the relatively smaller difference between medium and large companies (0.24) might indicate that the transition from partial to full automation becomes increasingly challenging as the scale of operations expands.

The use of digital technologies in selected stages of production varies depending on the size of the company (Figure 4). The analysis reveals that large companies demonstrate the highest level of digitalisation across all examined areas, with a score of 3.38. Medium companies show a moderate level of digitalisation (from 1.94 to 2.12), while small companies demonstrate the lowest level of digital technology adoption across all production stages. Their highest digitalisation level (1.81) was observed in "Procurement and transportation of raw materials" while the lowest (1.48) was in "Recycling and waste disposal".

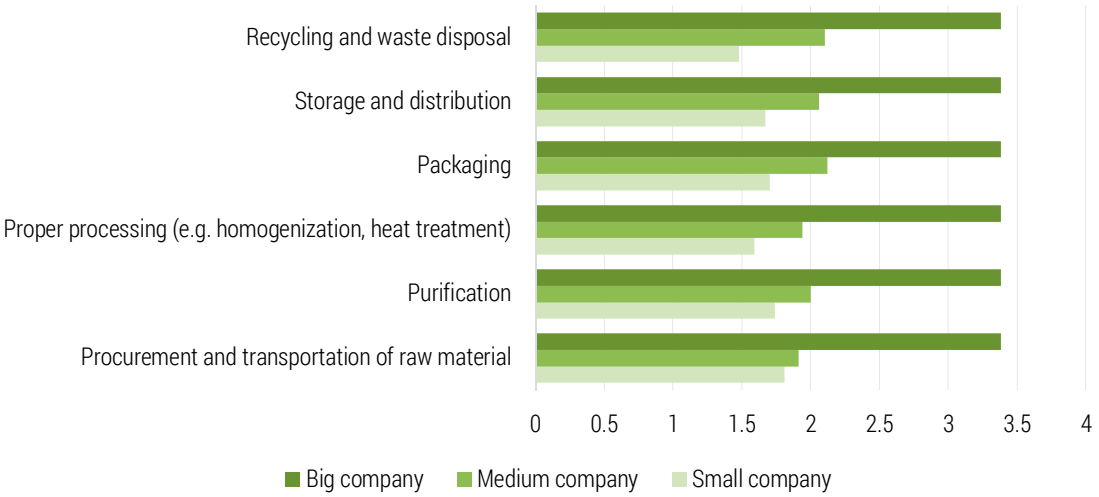

Figure 4. Level of use of digital technologies at selected stages of the production process. 1 very low, 2 low, 3 high, 4 very high, 0 don't know/don't have an opinion.

The level of adoption of various Industry 4.0 technologies in companies of different sizes – large, medium, and small – is illustrated in Figure 5. The data highlights how the implementation of these technologies varies depending on the size of the organisation in Poland.

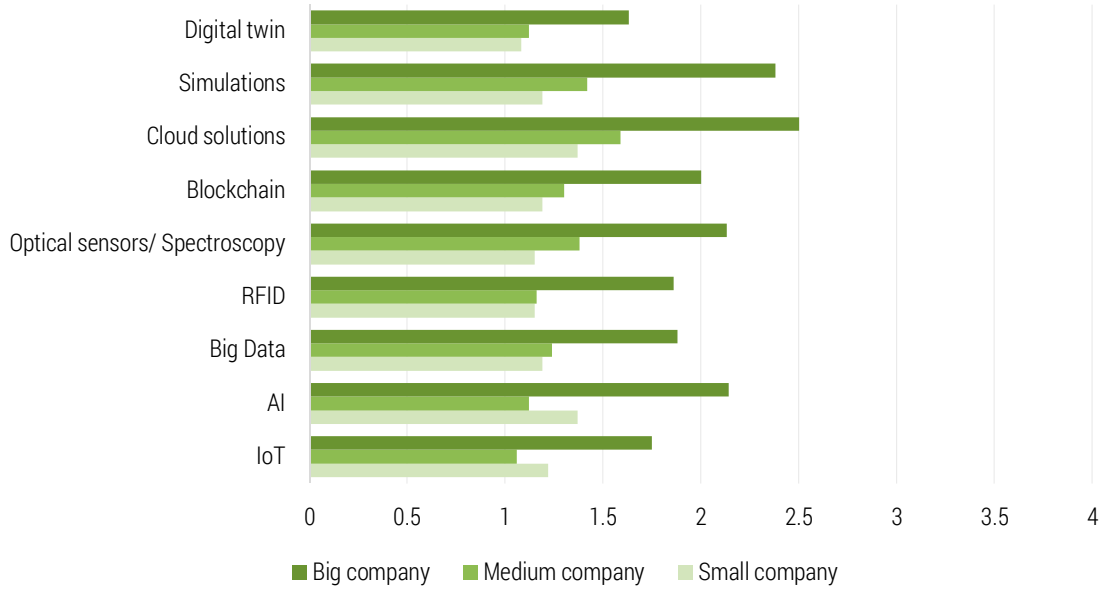

Figure 5. Level of use of particular technologies in companies. 1 no use, 2 experimental use, 3 regular use, 4 Intensive, systematic use, 0 don't know/no opinion.

DOI: 10.34659/eis.2025.94.3.1081

The largest companies achieved the highest rates of digital technology adoption across nearly all categories. Cloud solutions and simulations are notable, with average usage scores approaching 2.5. This indicates that these technologies are not yet used regularly, but their degree of experimentation is quite high. AI, optical sensors/spectroscopy, and blockchain, with ratings approaching from 2 to 2.14, indicate experimental use. The digital twin, RFID, Big Data, and IoT, with average scores between 1.63 and 1.88, suggest a shift from not used to experimental application. The higher adoption rates of advanced technologies suggest that big companies have more resources to invest in these technologies. This can lead to increased efficiency, better decision-making, and a competitive edge in the market. Medium-sized companies exhibit lower levels of adoption of digital technologies. In this category, cloud solutions, simulations, and optical sensors/spectroscopy are the most prevalent, with an average rating of approximately 1.46, indicating that they are shifted from not used to an experimental basis. The rest of the digital technologies aren't used much, if at all. Medium-sized companies should carefully analyse their needs and prioritise investments in technologies that will bring the most significant operational and strategic benefits. Focusing on technologies that can substantially improve efficiency and competitiveness is crucial.

The use of digital technology is lowest among small companies, where respondents' answers ranged from 1 to 1.5. This means that most of the technologies mentioned are not used in companies. Small companies should carefully prioritise their technological investments to focus on areas that will provide the most significant benefits. This could involve starting with cost-effective solutions that can be scaled up as the company grows.

Industry 4.0 opportunities and barriers in the context of sustainable production

The impact of Industry 4.0 technologies on various aspects of sustainable production in Poland's dairy industry, categorised by company size, was presented in Figure 6. The data reveals considerable disparities in the degree of benefit derived by each group, with larger companies exhibiting the most substantial advantages.

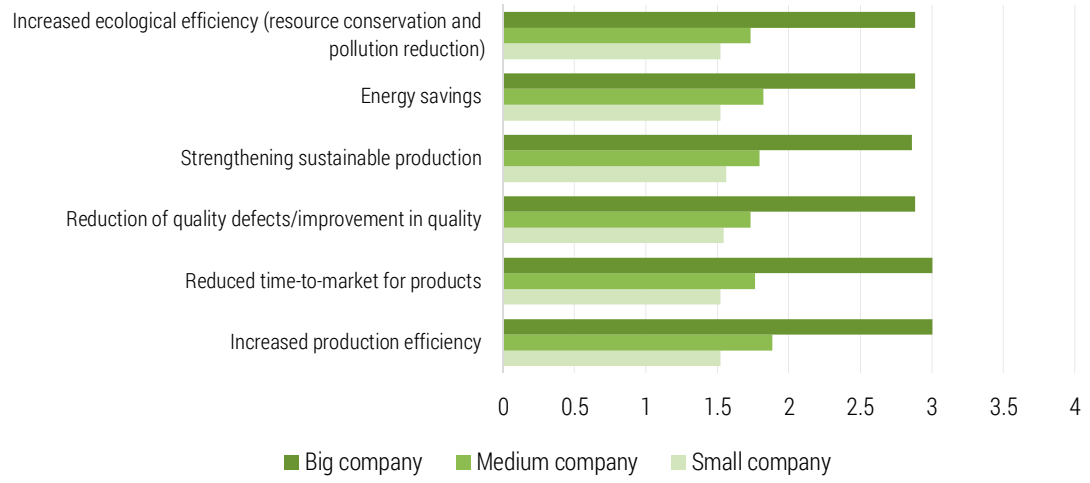

Figure 6. The impact of 4.0 technology on aspects of sustainable production. 1 no positive impact, 2 positive impact to a narrow extent, 3 positive impact, 4 strong positive impact, 0 don't know/ don't have an opinion.

The largest companies report the highest positive impact across all examined areas, with scores consistently close to 3 (positive impact). Notably, the greatest improvement is observed in increased production efficiency and reduced time to market for products. Furthermore, other areas, such as increased ecological efficiency, energy savings, strengthening sustainable production, and reduction of quality defects, also demonstrate considerable benefits, with values ranging between 2.86 and 2.88. This indicates that larger companies are more effectively able to utilise digital technologies to optimise their operations and enhance sustainability.

DOI: 10.34659/eis.2025.94.3.1081

Medium-sized companies, while not achieving the same levels of impact as large companies, still experience moderate benefits from digitalisation. The most significant advancements for these companies are observed in improved product and service innovation, which attained a score of 1.94, and customer satisfaction, which reached 1.91. Other domains, such as risk reduction and energy savings, also demonstrate discernible positive outcomes, although the impact is typically less pronounced than in large organisations. These findings suggest that medium-sized businesses are deriving benefits from digital technologies but may encounter constraints in fully harnessing their potential due to resource limitations or implementation challenges.

In contrast, the smallest companies report the lowest impact across all categories, with scores generally ranging from 1.48 to 1.56. The most significant benefits for small companies are observed in the strengthening of sustainable production and the reduction of quality defects, which scored 1.56 and 1.54, respectively. Nevertheless, the lowest values were observed in the areas of risk reduction and product and service innovation.

In the domain of sustainability, specifically in the areas of sustainable production and ecological efficiency, there is a discernible trend whereby larger companies derive greater benefits. Large companies achieve scores of 2.86 and 2.88 in these categories, respectively, which serves to illustrate the role of digital technologies in supporting environmental initiatives and resource conservation on a large scale. Medium producers demonstrate moderate improvements in these areas, whereas small companies exhibit minimal gains.

The adoption of Industry 4.0 technologies is often accompanied by a series of complex and interrelated challenges such as: (1) slow implementations, (2) resistance to change, (3) the complexity of systems, (4) lack of employee adoption, (5) high costs, and (6) cybersecurity risks (Sharma et al., 2023). Challenges can arise from barriers, so when a barrier exists, it often creates a challenge for the company. Figure 7 illustrates the key barriers faced by companies of varying sizes – small, medium, and large – in implementing digital technologies.

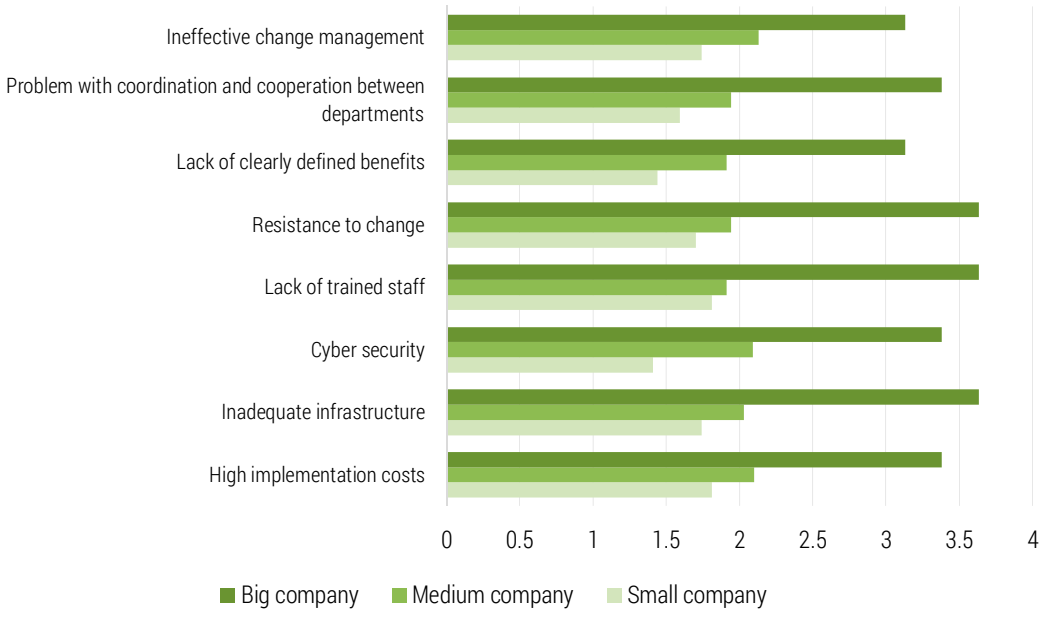

Figure 7. Implementation barriers and their impact on the implementation of technology 4.0. 1 very low, 2 low, 3 high, 4 very high, 0 don't know/ don't have an opinion.

The results reveal that while barriers are present across all company types, their intensity varies depending on organisational scale, with larger companies often reporting higher levels of difficulty in several areas. For example, high implementation costs are a more significant barrier for large companies, which scored 3.38, while medium and small companies scored 2.1 and 1.81, respectively. This difference may be due to the larger scale of operations and more complex systems in large compa-

DOI: 10.34659/eis.2025.94.3.1081

nies. Inadequate infrastructure is also a bigger problem for large companies, which scored 3.63, compared to 2.03 for medium companies and 1.74 for small companies. This suggests that larger companies have more complex infrastructure needs that are harder to meet. Cybersecurity concerns are more pronounced in large companies, which scored 3.38, while medium companies scored 2.09 and small companies 1.41. This indicates that larger companies may have more data and more complex systems to protect. The lack of trained staff is a critical issue for large companies, which scored 3.63, compared to 1.91 for medium companies and 1.81 for small companies. This highlights the need for better training programs and recruitment strategies in larger companies. Resistance to change is more evident in large companies, which scored 3.63, compared to 1.94 for medium companies and 1.7 for small companies. This suggests that larger companies may need more support in promoting a culture open to change. The lack of clearly defined benefits is another area where large companies struggle, scoring 3.13, compared to 1.91 for medium companies and 1.44 for small companies. This indicates that large companies need more clearly defined benefits to justify the implementation of new initiatives. Coordination and cooperation issues between departments are more severe in large companies, which scored 3.38, compared to 1.94 for medium companies and 1.59 for small companies. This suggests that larger companies may have more complex organisational structures, leading to greater challenges in this area. Ineffective change management is a significant challenge for large companies, which scored 3.13, compared to 2.13 for medium companies and 1.74 for small companies. This indicates a need for better change management strategies in larger companies.

Discussion, limitations, and future research directions

Our research results highlight significant differences in the adoption of Industry 4.0 technologies across company sizes in the Polish dairy industry. Larger companies demonstrate higher levels of digitalisation, deriving greater benefits in production efficiency, sustainability, and ecological impact. Medium companies show moderate progress, while small companies face substantial barriers, with limited adoption of digital technologies. High costs, lack of infrastructure, and employee-related challenges are the primary obstacles to implementing these solutions.

The findings of the research on the application of digital technologies are consistent with the work of Horváth and Szabó (2019), who argue that financial and profitability driving forces are not a priority for SMEs. They tend to adopt new digital technologies not primarily to reduce costs but to address other barriers, such as labour shortages. Their profitability expectations are lower, and they frequently engage in projects with modest returns to fulfil personal or management objectives.

The emerging technologies of Industry 4.0 can completely transform the manufacturing value chain. The integration of IoT and other digital technologies streamlines logistics, enhances transparency, and supports sustainability efforts in supply chain management. Our research shows that entrepreneurs, especially in large companies, are aware of the benefits of implementing Industry 4.0 technologies at various stages of the value chain. This transformation allows for real-time data collection and analysis, improving decision-making and responsiveness (T. Ch. Anil Kumar & L Bharani, 2024). This is consistent with the findings presented by Młody et al. (2023), who demonstrated that technologies such as Big Data Analytics, Business Intelligence, and machine-to-machine integration support faster and more accurate decision-making across various stages of the value chain. Obtained research results related to the impact of 4.0 technology on aspects of sustainable production align with Wiater et al. (2019) recommendations, which highlight the importance of focusing on reducing energy consumption and minimising emissions from production processes, particularly those related to heat energy generation.

The benefits of digitalisation are noteworthy because they create opportunities for companies to become "smart. Many companies are using digitalisation to enhance the efficiency of their factories, which enables them to achieve much higher levels of flexibility and better adapt to changes in consumer demand (Sony, 2020). Digital transformation also offers opportunities for companies to become more sustainable (el Hilali et al., 2020). Some of the benefits discussed in the literature include reducing energy consumption, reducing waste, and increasing energy efficiency (Sony, 2020). In the same vein, Abir (2024) highlights that Industry 4.0 promotes sustainable manufacturing by reducing material and energy waste while enabling circular economic flows, with technologies such

DOI: 10.34659/eis.2025.94.3.1081

as AI and robotics contributing to more sustainable production processes. One of the most significant barriers to digital transformation for companies is the high cost of implementation, particularly for large organisations. While they have access to more resources, the scale and complexity of their efforts often make costs prohibitive. This aligns with Horváth and Szabó's (2019) findings, which highlight financial constraints and limited profitability as major challenges for SMEs. These companies frequently struggle to invest in new technologies, relying instead on external funding like grants and tenders, which often have significant shortcomings. Inadequate infrastructure is another major obstacle, with large companies more affected than medium-sized or small companies due to the demands of integrating digital solutions into complex systems. Cybersecurity concerns are also more pronounced in larger companies, stemming from their expansive digital footprint and the critical nature of the data they handle. Human-related barriers, such as a lack of skilled personnel and resistance to change, are consistent across all company sizes but slightly more challenging for medium and large companies.

This highlights the universal need for training programs and effective change management strategies. Large organisations face additional challenges with coordination and cooperation due to the complexity of their structures, while smaller companies experience fewer such issues thanks to simpler frameworks. The findings partially align with the conclusions of Horváth and Szabó (2019). Management barriers are particularly critical for SMEs, as leaders often fail to recognise the potential of Industry 4.0 technologies.

One of the key sources of support for Polish entrepreneurs is regional and EU programs, which help overcome financial barriers associated with implementing digital technologies. In 2024, many industries, including agriculture, dairy, and the food industry, benefited from EU grants.

The funding opportunities for 2025 will cover a wide range of initiatives supporting business development, including financing research and development (R&D) projects, implementing research results, purchasing intangible assets and intellectual property (e.g., licenses, patents), expanding infrastructure, improving energy efficiency, and installing renewable energy sources. In Poland, one of the main support programs is the "European Funds for a Modern Economy (2021-2027)" program (FENG, 13 march 2025). Its goal is to accelerate Poland's economic growth by funding research, innovation, and technological investments. As part of this program, the "Ścieżka SMART" offers comprehensive support for SMEs, enabling them to carry out R&D projects and implement product and process innovations (PARP, 13 March 2025). Additionally, the Industrial Development Agency (ARP) has launched the "DIG.IT" program, designed for micro, small, and medium-sized enterprises across Poland. This program supports the purchase of digital technologies, such as software, IT equipment, and employee training. The maximum funding amount is €200,000, covering up to 50% of the investment value (ARP, 13 March 2025).

Within regional initiatives, each voivodeship develops tailored programs that address the specific needs of the local economy and development priorities. In 2025, various initiatives are planned to support business digitalisation, tailored to different business groups and economic sectors. A particularly relevant EU program for the food industry is "NUTRITECH", led by the National Centre for Research and Development (NCBiR). Its goal is to increase the availability of nutritional products and technologies that promote proper nutrition. This program will be held until 2030 (GOV.PL, 13 March 2025).

Concluding, our findings are consistent with those of Narkhede et al. (2023), who argue that, despite the transformative potential, challenges such as high initial investment costs, the need for specialised skills, and cybersecurity threats pose significant barriers, particularly for small and SMEs.

This study offers valuable insights into the adoption of Industry 4.0 technologies in the Polish dairy industry; however, certain limitations warrant consideration and highlight avenues for future research. First, the study's limited sample size and its focus on the Polish dairy sector restrict the generalizability of the findings. Expanding the scope to include a larger and more geographically diverse sample (i.e. other agri-food sectors) would enhance the applicability of results. Second, while the study evaluates Industry 4.0 technologies, it does not isolate the specific impacts of individual technologies such as blockchain or AI.

Future research should address these distinctions to better understand their unique contributions to sustainability and efficiency. Finally, integrating qualitative methods, such as case studies or interviews, could provide richer insights into organisational and cultural barriers, while exploring

DOI: 10.34659/eis.2025.94.3.1081

the influence of regulatory frameworks and financial incentives could reveal pathways to support technology adoption, particularly in SMEs.

Conclusions

Our research provides valuable guidance for managerial decision-making related to Industry 4.0 technologies in the dairy industry, emphasising both opportunities and challenges. The primary objective of this study was to examine how companies manage the opportunities and barriers of digital transformation while meeting the demands of sustainable management. Our findings confirm that this objective has been achieved, as the study identifies key factors influencing digital transformation adoption, highlights company size-dependent challenges, and offers practical recommendations to address them. The results demonstrate that while Industry 4.0 technologies provide significant benefits, including process optimisation, cost reduction, improved sustainability, and enhanced ecological performance, their implementation is often hindered by financial constraints, skills shortages, and organisational resistance. Furthermore, the study reveals substantial disparities between large companies and SMEs regarding digital transformation progress, investment capacity, and the ability to overcome technological barriers. By addressing these challenges and proposing targeted strategies, our research effectively contributes to bridging the gap between digitalisation and sustainable management in the dairy sector.

Large enterprises demonstrate a higher degree of digitalisation and derive notable benefits from Industry 4.0 technologies, such as increased production efficiency, sustainability improvements, and better decision-making through data-driven processes. However, they face substantial challenges related to high implementation costs, interdepartmental coordination difficulties, and cybersecurity risks. In contrast, SMEs are significantly behind in adopting digital technologies due to limited financial and human resources. They exhibit lower levels of automation and struggle with a lack of expertise in implementing advanced digital solutions. Our results indicate that SMEs primarily rely on external support to initiate digital transformation, underscoring the need for accessible financial aid and tailored training programs.

One of the most significant barriers remains the high costs of implementing Industry 4.0 technologies, particularly for large companies facing substantial upfront investments. To mitigate this challenge, managers should seek external funding sources such as grants and subsidies, while also adopting phased implementation strategies that start with pilot projects to manage financial risks. Several financial support programs are available, including the Operational Program Smart Growth, which funds R&D initiatives, the Industry 4.0 Sector Fund, and regional innovation programs. SMEs and startups can benefit from targeted funding such as the EIC Accelerator and PARP innovation vouchers.

The research also confirms that the lack of digital competencies among employees and resistance to technological change are major obstacles to successful transformation. Companies should focus on continuous workforce development through structured training programs, collaboration with educational institutions, and internal upskilling initiatives. These measures can help employees acquire the necessary expertise to work with advanced digital technologies while fostering a culture of adaptability. Larger organisations, in particular, should implement comprehensive change management strategies to ensure smooth transitions and reduce resistance to digital adoption.

In addition to financial and workforce challenges, companies must prioritise infrastructure modernisation and cybersecurity investments to successfully integrate new technologies into their operations. Ensuring robust data protection measures and secure digital environments will be crucial to maintaining operational efficiency and regulatory compliance. Aligning digital transformation with sustainability goals – such as energy efficiency, waste reduction, and resource optimisation – will enable companies to enhance their ecological performance while improving competitiveness.

Scientifically, the study contributes to understanding the integration of digital transformation and sustainability, demonstrating how Industry 4.0 technologies optimise processes and meet environmental standards. It highlights size-dependent adoption challenges, with large firms facing coordination and integration complexities, while SMEs struggle with resource limitations. Moreover, our findings emphasise the need for further exploration of specific Industry 4.0 technologies, such as

DOI: 10.34659/eis.2025.94.3.1081

blockchain and AI, to quantify their impact on sustainability metrics, including energy efficiency, resource management, and waste reduction.

By providing practical, step-by-step recommendations, including targeted funding strategies, phased implementation approaches, workforce training, and sustainability alignment, this study offers a structured framework for companies – particularly those with limited financial and human resources – to navigate the challenges of digital transformation in the Industry 4.0 era. Our findings confirm that while digitalisation presents significant advantages, its successful implementation requires strategic planning, tailored support mechanisms, and ongoing adaptation to evolving technological and sustainability demands.

Acknowledgements

Supported by funds granted by the National Science Centre, under the "Miniatura 7" Programme (2023/07/X/HS4/00223). Project title "Digital transformation of the food industry in Poland and its impact on sustainable production management".

Supported by funds granted by the Minister of Science of the Republic of Poland under the „Regional Initiative for Excellence" Programme for the implementation of the project "The Poznań University of Economics and Business for Economy 5.0: Regional Initiative – Global Effects (RIGE)".

The contribution of the authors

Conceptualisation, K.W., M.M., M.S.; literature review, K.W., M.M., M.S.; methodology, K.W., M.M., M.S.; formal analysis, K.W., M.M., M.S.; writing, K.W., M.M., M.S.; conclusions and discussion, K.W., M.M., M.S.

The authors have read and agreed to the published version of the manuscript.

References

Abir, A. (2024). *Industry 4.0 Technologies for a Data-Driven, Secure, Green and Circular Manufacturing Economy*. https://doi.org/10.1109/GreenTech58819.2024.10520440

Argilovski, A., Jovanoski, B., & Minovski, R. (2023). *An overview of the Digital Transformation and Industry 4.0 technologies implementation frameworks*. https://doi.org/10.24867/IS-2023-T1.1-7_03841

ARP. (13 March 2025). *Agencja Rozwoju Przemysłu*. https://arp.pl/pl/dla-biznesu/wsparcie-innowacji/granty-na-cyfryzacje/

Barłowska, J., Szwajkowska, M., Litwińczuk, Z., & Król, J. (2011). Nutritional Value and Technological Suitability of Milk from Various Animal Species Used for Dairy Production. Comprehensive Reviews in Food Science and Food Safety, 10, 291-302. https://doi.org/10.1111/j.1541-4337.2011.00163.x

Ejdys, J., & Szpilko, D. (2022). European Green Deal – research directions. a systematic literature review. Economics and Environment, 81(2), 8-38. https://doi.org/10.34659/eis.2022.81.2.455

el Hilali, W., Manouar, A., & Idrissi, M. (2020). Reaching sustainability during a digital transformation: a PLS approach. International Journal of Innovation Science, ahead-of-print. https://doi.org/10.1108/IJIS-08-2019-0083

Feil, A. A., do Amaral, C. C., Walter, E., Bagatini, C. A., Schreiber, D., & Maehler, A. E. (2023). Set of sustainability indicators for the dairy industry. Environmental Science and Pollution Research, 30(18), 52982-52996. https://doi.org/10.1007/s11356-023-26023-3

FENG. (13 march 2025). *Fundusze Europejskie dla Nowoczesnej Gospodarki*. https://www.nowoczesnagospodarka.gov.pl/

Fiorillo, V., & Amico, B. M. (2024). Milk Quality and Economic Sustainability in Dairy Farming: A Systematic Review of Performance Indicators. Dairy, 5(3), 384-402. https://www.mdpi.com/2624-862X/5/3/31

GOV.PL. (13 March 2025). *Nutritech*. https://www.gov.pl/web/ncbr/nutritech

Groves, R. M., & Mathiowetz, N. A. (1984). Computer Assisted Telephone Interviewing: Effects on Interviewers and Respondents. Public Opinion Quarterly, 48(1B), 356-369. https://doi.org/10.1093/poq/48.1B.356

Hassoun, A., Aït-Kaddour, A., Abu-Mahfouz, A. M., Rathod, N. B., Bader, F., Barba, F. J., Biancolillo, A., Cropotova, J., Galanakis, C. M., Jambrak, A. R., Lorenzo, J. M., Måge, I., Ozogul, F., & Regenstein, J. (2022). The fourth industrial revolution in the food industry – Part I: Industry 4.0 technologies. Critical Reviews in Food Science and Nutrition, 1-17. https://doi.org/10.1080/10408398.2022.2034735

Hassoun, A., Bekhit, A., Režek Jambrak, A., Regenstein, J., Chemat, F., Morton, J., Gudjonsdottir, M., Rodríguez, M., Prieto, M., Varela, P., Arshad, R., Bhat, Z., & Ueland, Ø. (2022). The fourth industrial revolution in the food industry – Part II: Emerging food trends. Critical Reviews in Food Science and Nutrition. https://doi.org/10.1080/10408398.2022.2106472

Hassoun, A., Garcia-Garcia, G., Trollman, H., Jagtap, S., Parra-López, C., Cropotova, J., Bhat, Z., Centobelli, P., & Aït-Kaddour, A. (2023). Birth of dairy 4.0: Opportunities and challenges in adoption of fourth industrial revolution technologies in the production of milk and its derivatives. Current Research in Food Science, 7, 100535. https://doi.org/https://doi.org/10.1016/j.crfs.2023.100535

Hassoun, A., Jagtap, S., Trollman, H., Garcia-Garcia, G., Abdullah, N. A., Goksen, G., Bader, F., Ozogul, F., Barba, F. J., Cropotova, J., Munekata, P. E. S., & Lorenzo, J. M. (2023). Food processing 4.0: Current and future developments spurred by the fourth industrial revolution. Food Control, 145, 109507. https://doi.org/https://doi.org/10.1016/j.foodcont.2022.109507

Horváth, D., & Szabó, R. Z. (2019). Driving forces and barriers of Industry 4.0: Do multinational and small and medium-sized companies have equal opportunities? Technological Forecasting and Social Change, 146, 119-132. https://doi.org/https://doi.org/10.1016/j.techfore.2019.05.021

Javaid, M., Haleem, A., Singh, R., Suman, R., & Santibanez Gonzalez, E. (2022). Understanding the adoption of Industry 4.0 technologies in improving environmental sustainability. Sustainable Operations and Computers, 3. https://doi.org/10.1016/j.susoc.2022.01.008

Kim, S., Choi, B., & Lew, Y. K. (2021). Where Is the Age of Digitalization Heading? The Meaning, Characteristics, and Implications of Contemporary Digital Transformation. Sustainability, 13(16), 8909. https://www.mdpi.com/2071-1050/13/16/8909

Konstantinidis, F. K., Balaska, V., Symeonidis, S., Tsilis, D., Mouroutsos, S. G., Bampis, L., Psomoulis, A., & Gasteratos, A. (2023). Automating dairy production lines with the yoghurt cups recognition and detection process in the Industry 4.0 era. Procedia Computer Science, 217, 918-927. https://doi.org/https://doi.org/10.1016/j.procs.2022.12.289

Krajewski, K. (2023). Perspektywy dla Przemysłu 4.0 w przetwórstwie mleczarskim, Część I -Podstawy procesów innowacyjnych w przetwórstwie mleka. Mleczarskie Technologie(2), 36-38. https://www.spozywczetechnologie.pl/mleko/wiadomosci-z-branzy-mleczarskiej/940/perspektywy-dla-przemyslu-4-0-w-przetworstwie-mleczarskim-czesc-i-podstawy-procesow-innowacyjnych-w-przetworstwie-mleka

Malik, M., Gahlawat, V. K., Mor, R. S., & Hosseinian-Far, A. (2024). Towards white revolution 2.0: challenges and opportunities for the industry 4.0 technologies in Indian dairy industry. Operations Management Research, 17(3), 811-832. https://doi.org/10.1007/s12063-024-00482-4

Matuszak-Flejszman, A., Paliwoda, B., & Banach, J. (2024). Factors influencing the environmental effectiveness of the dairy industry in Poland. Scientific Papers of Silesian University of Technology Organization and Management Series, 275-297. https://doi.org/10.29119/1641-3466.2023.184.14

Mavani, N., Mohd Ali, J., Othman, S., Hussain, M., Hashim, H., & Abd.Rahman, N. (2022). Application of Artificial Intelligence in Food Industry – a Guideline. Food Engineering Reviews, 14. https://doi.org/10.1007/s12393-021-09290-z

Młody, M., Ratajczak-Mrozek, M., & Sajdak, M. (2023). Industry 4.0 technologies and managers' decision-making across value chain. Evidence from the manufacturing industry. Engineering Management in Production and Services, 15, 2023. https://doi.org/10.2478/emj-2023-0021

Narkhede, G., Mahajan, S., Narkhede, R., & Chaudhari, T. (2023). Significance of Industry 4.0 technologies in major work functions of manufacturing for sustainable development of small and medium-sized enterprises. Business Strategy & Development, 7. https://doi.org/10.1002/bsd2.325

Neethirajan, S. (2024). Net Zero Dairy Farming – Advancing Climate Goals with Big Data and Artificial Intelligence. Climate, 12(2), 15. https://www.mdpi.com/2225-1154/12/2/15

Oztemel, E., & Gursev, S. (2020). Literature review of Industry 4.0 and related technologies. Journal of Intelligent Manufacturing, 31(1), 127-182. https://doi.org/10.1007/s10845-018-1433-8

PARP. (13 March 2025). *Polska Agencja Rozwoju Przedsiębiorczości*. https://www.parp.gov.pl/component/grants/grantss?sort=default&category%5B%5D=6&term%5B%5D=1&text_search=

Samson, T. K., Omoyajowo, A. C., Adebayo, S., & Salawu, S. O. (2023). Smart modelling of dairy milk production with machine learning. IOP Conference Series: Earth and Environmental Science, 1219(1), 012008. https://doi.org/10.1088/1755-1315/1219/1/012008

Sharma, M., Joshi, S., & Govindan, K. (2023). Overcoming barriers to implement digital technologies to achieve sustainable production and consumption in the food sector: A circular economy perspective. Sustainable Production and Consumption, 39, 203-215. https://doi.org/https://doi.org/10.1016/j.spc.2023.04.002

Sinha, B. B., & Dhanalakshmi, R. (2022). Recent advancements and challenges of Internet of Things in smart agriculture: A survey. Future Generation Computer Systems, 126, 169-184. https://doi.org/https://doi.org/10.1016/j.future.2021.08.006

Sony, M. (2020). Pros and cons of implementing Industry 4.0 for the organizations: a review and synthesis of evidence. Production & Manufacturing Research, 8(1), 244-272. https://doi.org/10.1080/21693277.2020.1781705

Tangorra, F. M., Buoio, E., Calcante, A., Bassi, A., & Costa, A. (2024). Internet of Things (IoT): Sensors Application in Dairy Cattle Farming. Animals, 14(21), 3071. https://www.mdpi.com/2076-2615/14/21/3071

Usman, A.K., Shourav Md Hasibul Hasan, Anil Kumar, T.Ch.,Thilagham, K.T., Ravikumar, N., & Bharani, L. (2024). IoT and Industry 4.0: Revolutionizing Manufacturing Processes and Supply Chains. Journal of Informatics Education and Research, 4(3). https://doi.org/10.52783/jier.v4i3.1425

Varriale, V., Cammarano, A., Michelino, F., & Caputo, M. (2024). The role of digital technologies in production systems for achieving sustainable development goals. Sustainable Production and Consumption, 47, 87-104. https://doi.org/https://doi.org/10.1016/j.spc.2024.03.035

Vp, A., Singh, S., & Chauhan, A. (2022). Blockchain Technology in Dairy Industry. 74, 52-57.

Wiater, J., Boruszko, D., Dąbrowski, W., Żyłka, R., & Antonowicz, S. (2019). Evaluation of sustainable development of dairy industry in Poland. Economics and Environment, 69(2), 13. https://ekonomiaisrodowisko.pl/journal/article/view/91

Wichmann, R. L., Eisenbart, B., & Gericke, K. (2019). The Direction of Industry: A Literature Review on Industry 4.0. Proceedings of the Design Society: International Conference on Engineering Design, 1(1), 2129-2138. https://doi.org/10.1017/dsi.2019.219

Wójcicki, K., Biegańska, M., Paliwoda, B., & Górna, J. (2022). Internet of Things in Industry: Research Profiling, Application, Challenges and Opportunities – A Review. Energies, 15(5), 1806. https://www.mdpi.com/1996-1073/15/5/1806

Wójcicki, K., Górna, J., & Sikorska, E. (2024). Digitalisation in agri-food sector. In K. Pawlak-Lemańska, B. Borusiak & E. Sikorska (Eds.), S*ustainable food: Production and consumption perspectives* (pp. 41–53). Poznań University of Economics and Business Press. https://doi.org/10.18559/978-83-8211-209-2/3

Zheng, T., Ardolino, M., Bacchetti, A., & Perona, M. (2021). The applications of Industry 4.0 technologies in manufacturing context: a systematic literature review. *I*nternational Journal of Production Research, 59(6), 1922-1954. https://doi.org/10.1080/00207543.2020.1824085

Ziętara, W., Pietrzak, M., & Malak-Rawlikowska, A. (2024). Polish Dairy Farm Transformations and Competitiveness 20 Years after Poland's Accession to the European Union. Animals (Basel), 14(13). https://doi.org/10.3390/ani14132013

Krzysztof WÓJCICKI • Michał MŁODY • Maja SAJDAK

SZANSE I BARIERY CYFROWEJ TRANSFORMACJI PRZEMYSŁU MLECZARSKIEGO I JEJ WPŁYW NA ZRÓWNOWAŻONE ZARZĄDZANIE PRODUKCJĄ

STRESZCZENIE: Badanie analizuje poziom implementacji technologii Przemysłu 4.0 w polskim przemyśle mleczarskim oraz ich wpływ na zrównoważone zarządzanie produkcją, uwzględniając szanse, bariery oraz implikacje strategiczne. Przeprowadzono ustrukturyzowaną ankietę CATI z 68 firmami mleczarskimi. Dane ilościowe przeanalizowano przy użyciu statystyk opisowych i oceniono rozbieżności w zakresie wdrażania technologii i ich wpływu na wyniki w zakresie zrównoważonego rozwoju. Duże firmy wykazały wyższy poziom cyfryzacji, czerpiąc korzyści ze zwiększonej wydajności, zrównoważonego rozwoju i wydajności ekologicznej. Małe i MŚP napotykają bariery, takie jak wysokie koszty, ograniczona infrastruktura i wyzwania związane z siłą roboczą. Przyszłe badania powinny zbadać konkretne technologie, takie jak blockchain i sztuczna inteligencja, oraz rozszerzyć je na inne sektory w celu uzyskania szerszego wglądu. Wyniki badań podkreślają potrzebę wsparcia finansowego, programów szkoleniowych i dostosowanych strategii w celu przezwyciężenia barier, szczególnie dla MŚP. Nasze badania wypełniają lukę między transformacją cyfrową a zrównoważonym rozwojem w sektorze mleczarskim, oferując praktyczne spostrzeżenia dla menedżerów i decydentów.

SŁOWA KLUCZOWE: transformacja cyfrowa, Przemysł 4.0, mleczarstwo, zrównoważony rozwój

DOI: 10.34659/eis.2025.94.3.1081

DOI: 10.34659/eis.2025.94.3.1081