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Contact to corresponding author: Dániel Fróna, frona.daniel@econ.unideb.hu

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Dániel Fróna

University of Debrecen, Hungary

 orcid.org/0000-0003-4872-0018

János Szenderák

University of Debrecen, Hungary

 orcid.org/0000-0003-4252-2125

Digitalization and digital technologies: The obstacles to adaptation among Hungarian farmers

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Abstract

Research background: Digital technologies aim to enhance efficiency, competitiveness, and sustainability. Despite ongoing efforts, Hungary is encountering various challenges in digitalization. This research seeks to investigate the potential of digital technologies in addressing these challenges, with a particular focus on precision agriculture technologies (PA).

Purpose of the article: This study explores the utilization of digital technologies among 81 agricultural and food companies in Hungary. The study evaluates the use of advanced and less advanced digital technologies and their impact on rural areas. Additionally, the research seeks to understand the economic and social impacts resulting from the adoption of these technologies, focusing specifically on precision farming.

Methods: The study uses advanced clustering methods to categorize agricultural companies based on their use of digital technology. The research employed the two-step clustering method, which has been recognized for its robustness in clustering mixed-level variables.

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Findings & value added: Farmers and food producers generally have low adoption rates of advanced digital technologies, preferring common but less advanced tools. This is mainly due to high investment costs, economies of scale, limited experience and expertise, and a lack of willingness to cooperate among farmers. The respondents could be classified into two groups: one group is aware and even understands advanced technology, but rarely uses it. In contrast, the other group is largely unaware of these technologies. The results indicate that a lack of knowledge and expertise can significantly impede the adoption of advanced technologies in agriculture. Policymakers must develop a mix of policies that collectively reduce the economic barriers to technology adoption while engaging stakeholders who may not fully understand the benefits of advanced technologies.

Introduction

Digitalization is expected to significantly impact the agriculture and food sector, similar to its impact on other industries. The digitalization process could lead to a significant shift in the way agriculture produces, and it could offer a route for innovation and new ways of managing production and supply chains cost-effectively and sustainably. The agricultural sector is experiencing transformative changes due to digitalization, such as a stronger focus on precision agriculture, the incorporation of the Internet of Things (IoT), and the use of big data to improve production and business efficiencies (McFadden *et al.*, 2022). In the age of Big Data, the capacity to handle vast amounts of information in both agriculture and the food industry is becoming increasingly critical for sustaining competitiveness and market standing. One of the primary facets of the digital shift is data acquisition (Bronson & Knezevic, 2016; Kamilaris *et al.*, 2017; Osinga *et al.*, 2022). In recent years, those involved in agriculture have increasingly turned to digital tools to enhance their operations (Bramley & Trengove, 2013; Lu *et al.*, 2016), a shift that has been fast-tracked by the social distancing rules enforced during the COVID-19 pandemic (Galanakis *et al.*, 2021; Huang, 2020; McFadden *et al.*, 2022). Our research aims to evaluate the adoption and utilization of both standard and advanced technologies among stakeholders in the food and agriculture sector. Additionally, we are interested in their perceptions regarding the impact of technologies on rural and social development, a topic that is often overlooked in other research.

This research aims to measure the use and uptake of advanced and less advanced technologies, including precision agriculture. It also aims to understand the economic and social impacts expected from integrating these technologies. The two-step clustering method was used to analyze the an-

swers of 81 companies from the Hungarian agriculture sector. By doing this, it provides insights into the challenges and opportunities associated with the digital transformation of Hungarian agriculture. Our research is structured as follows: First, we will review the digitalization trends in the European Union and Hungary, focusing on the adoption and usage of technologies. Next, we will present the data and methods that were used. Then, we will provide detailed results of the two-step cluster analysis by question blocks and discuss the policy implications. Finally, we will offer suggestions for improving current digitalization policies in Hungary.

Literature review

The transformation of the European Union's agricultural sector through digital technology could bring enormous change, enhancing efficiency, sustainability, and competitiveness (Ehlers *et al.*, 2021). Advanced technologies such as artificial intelligence (AI), robotics, the Internet of Things (IoT), and 5G can provide invaluable assistance to farmers and agribusinesses (European Commission, 2023c). Digitalization can also streamline the value chain, fostering better collaboration and communication among producers, processors, distributors, and retailers (Butollo, 2021). Digitalization can provide a competitive edge to the agricultural sector in Europe by introducing innovative solutions and opening up new business avenues. Automating tasks and streamlining operations can lighten farmers' physical and mental burdens.

Furthermore, digitalization can enhance the traceability and transparency of agricultural products, empowering consumers to make well-informed decisions (European Commission, 2023d; Kosior, 2019; Rolandi *et al.*, 2021). By doing this, Europe's agricultural sector can fully leverage the benefits of the digital era, enhancing the sustainability and profitability of farming operations while tackling critical issues like food security and climate change (European Commission, 2023b). However, digitalization can also lead to a digital divide between those with access to these technologies and those without access (Vasilescu *et al.*, 2020). This divide can manifest between connected and unconnected farms and small and large farming operations. To make digitalization inclusive and accessible, policymakers, industry leaders, and technology providers must collaborate to promote

the advantages of digitalization and provide farmers with the necessary training, resources, and incentives to embrace new technologies.

A consistent finding in the literature is that the likelihood of adopting these tools tends to rise with the level of a farmer's human capital (Daberkow & McBride, 2003; Griffin *et al.*, 2017; Schimmelpfennig, 2016). The disparity in adopting digital technologies, often called the "digital divide," is primarily attributed to human capital variations, encompassing individuals' collective skills, knowledge, and other intangible assets (Yang *et al.*, 2021). In the agricultural sector, farmers' inherent competencies and understanding significantly influence their propensity to embrace digital innovations (Gabriel & Gandorfer, 2023). Consequently, an initial assessment of farmers' existing capabilities and the potential investment required to enhance these skills is a critical precursor to the digital transformation of agricultural practices (Khanna, 2021; Rijswijk *et al.*, 2021).

A network of connections was established based on the data retrieved from the WoS database to assess the state of the literature. The "agriculture + digitalization" keywords yielded 794 results between 2013 and 2023. All publishers and all areas were set as search parameters during the WoS search engine operation; the search was conducted in November 2023. This result can be observed in Figure 2. According to the results, digitalization has general, broad themes that are hard to classify or specify (such as big data or innovation). This may be a double-edged sword, since it implies general applicability, but stakeholders must translate these factors into practice-oriented and firm-specific solutions.

Despite the considerable heterogeneity in the data and methodologies employed in the related literature, several key facilitators, impediments, and limitations to adoption have been consistently identified that directly suggest potential policy intervention possibilities. Key areas worth policymakers' focus in the agricultural sector are related to connectivity, relevance, skills, cost, risk, and trust issues to facilitate the digitalization process (Figure 1). Digitalization has the potential to offer considerable environmental, social, and economic benefits. It can improve farmers' decision-making processes and farm efficiency while reducing costs, boosting production, and improving product quality. This may benefit the environment and food security due to less resource use and higher production. However, it can have harmful effects as well. There is a possibility for a more significant concentration on the market; it can further contribute to the divide between small-scale and large-scale farmers, while low-skilled farms and

farmers may have limited ability to adapt (Lioutas *et al.*, 2021). Strategies must enhance digital competencies, prevent or mitigate risks, and accommodate diversity to address policy gaps in the future (Ehlers *et al.*, 2022). Digital agriculture should be considered in a broad context. While most attention was paid to questions of resource use efficiency, other sustainability principles must also be considered. In addition, legal and regulatory developments are on the rise, but they are still highly fragmented. Data ownership regimes need to be established to enhance sustainability in the future (MacPherson *et al.*, 2022). Agricultural performance was highly variable in Europe, with Hungary among the relatively poor performers. It was found that countries with a young and better-trained farm workforce and a high level of farm investments were 9 to 12 times more likely to attain high economic performance compared to aging farms with low levels of education and investments (Giannakis & Bruggeman, 2015). In general, enterprises in Northern and Western Europe across all sectors have high or moderate levels of digitalization and robotization. In contrast, enterprises had relatively low levels of digitalization and robotization in Hungary (Brodny & Tutak, 2021). Similar tendencies were observed among European agri-food cooperatives, with varying levels of digitalization that correlated with the countries in which they operate (Jorge-Vázquez *et al.*, 2021). The digital divide issue must also be addressed within the context of research and development (Kovac *et al.*, 2024).

Digitalization in Hungary

The advancement of digital technologies and their applications is seen as a crucial element in fueling Hungary's economic progress and enhancing productivity in the agricultural sector (Kovács & Husti, 2018). According to the Hungarian Central Statistical Office (HCSO), farmers most often do their banking and e-government digitally. However, the results of the 2020 agricultural census show that more and more farms are using digital tools for farming, including tools related to precision agriculture and the use of extension services. Digital technology can help agriculture in several areas, such as increasing productivity, improving crop quality, reducing environmental impacts, and making farmers' work easier. However, small-scale farms face several challenges in the digital transition, such as high equipment costs, a lack of necessary skills, limited access to training and advice, and a lack of technological infrastructure (KSH, 2023). However, the value

and benefits of digital technologies need to be demonstrated more effectively, while digital investments must be incentivized and supported (Gaál *et al.*, 2021).

Earlier research highlighted areas for Hungarian agricultural policies to enhance their sustainability, such as strengthening the ecological approach, addressing climate change more efficiently, including complex landscape management, removing measures that exacerbate inequalities among farmers, and addressing issues related to healthy food consumption and food waste (Hoyk *et al.*, 2022).

Hungary's Common Agricultural Policy (CAP) Strategic Plan supports various interventions, including knowledge exchange and dissemination of information, digital transformation of agricultural holdings, advisory activities, and innovation collaborations. Specific resources will be allocated to foster innovation, and support for the digital transition will be provided to 1,600 farms. In addition, 736 210 individuals will gain from advice, training, and knowledge sharing supported by the CAP, focusing on environmental or climate-related performance. Hungary's CAP Strategic Plan was crafted to yield concrete outcomes aligned with EU-level CAP-specific goals while contributing to the European Green Deal. The plan presents opportunities to lessen reliance on synthetic fertilizers, increase renewable energy production without compromising food production, and transform the sector's capabilities with more sustainable production methods. Other EU instruments, such as the Recovery and Resilience Facility (RRF) or the European Structural and Investment Funds (ESIF), will also address the needs of rural areas (European Commission, 2023a).

Methods

Secondary and primary data collection

The secondary data utilized in the composition of this research was derived from relevant articles. The literature review process necessitated a thorough examination and analysis of the theoretical background and a search for relevant studies. The literature search predominantly used Google Scholar and Web of Science (WoS). In the context of Google Scholar, sorting was primarily based on relevance, with additional consideration given to the number of citations and the relevance of the publisher. As previously

noted, abundant international literature underscores the topic's significance.

As primary research, a questionnaire was conducted among Hungarian farmers. The potential respondent's data (e-mail and company profile) were obtained from the EMIS database provided by ISI Emerging Market Group Limited. To select companies, the filter of NAICS (North American Industry Classification System) branches was used, and only Hungarian companies were selected, with agriculture, forestry, fishery, and hunting as the main branches of activity (NAICS number 11). The profiles of 2 689 potential companies were matched after the settings. The questionnaire was designed to capture various aspects of digitalization in the agricultural sector, based on our previous, national level analysis, presented in Szenderák *et al.* (2021) (see Appendix). The questionnaire was sent to the companies by email to collect the information. The data was collected between February and April 2023, and 81 evaluable responses were received and evaluated.

The study employed the Two-Step Clustering method developed by Chiu *et al.* (2001), which is a robust procedure for clustering mixed-level variables. The cluster number selection is automatic; the procedure is highly scalable and accurate. The algorithm consists of two steps. First, the data records are scanned and the dense regions (subsets of the data space where observations are highly concentrated) of the records are stored in summary statistics. A collection of statistics summarizes these regions' characteristics, which is called the cluster feature CF_j of a cluster C_j . A Cluster Feature (CF) Tree is constructed in the next step, a data structure that compresses the dataset by grouping records into the so-called pre-clusters. This step makes the clustering procedure more efficient because the number of dense regions is far less than the number of data records. In the second step, the pre-clusters are iteratively merged. Hierarchical clustering algorithm is applied to each dense region treated as an individual data point. The distance measure used is based on the idea that the log-likelihood changes due to merging two clusters. Determining the number of clusters is usually left to the researcher, which may result in subjective choices. However, one great advantage of this procedure is that it automatically determines the number of clusters based on information criteria and then assigns each data record to a cluster. The clustering algorithm measured the quality of the clusters. In all cases, cluster quality was deemed to be fair.

Furthermore, the algorithm was found to have a much lower error rate than usual clustering algorithms, such as *k*-means. Chiu *et al.* (2001) reported that the algorithm could identify the true clusters for about 98% of the generated datasets. One drawback of this approach is that it assigns too much weight to categorical variables (Bacher *et al.*, 2004), potentially impacting the results for the sales per capita variable, the only continuous variable in the dataset. In our previous research, including Szenderák *et al.* (2021), we found that while there were several apparent factors contributing to the lack of precision agriculture adoption, others were highly firm-specific, such as farm size and structure, and the farmer's assessment of technologies. Thus, we used clustering methods to identify the fundamental factors influencing the responses, which we expected to be heterogeneous and noisy.

The following leading indicators were used during the clustering from $N = 81$ companies altogether:

- *the natural logarithm of sales/capita*: the natural logarithms of the ratio of last year's net sales divided by the number of employees
- *profile*: the companies' main activity, which provided at least 66% of net sales (1 = animal husbandry, 2 = crop production, and 3 = horticulture, mixed and other)
- *block questions* (USE, UPTAKE, EFFECT, PA)

The four blocks of questions consisted of the following items:

- *USE*: How often do you use the following digital technologies in your business? (Questions were rated on a scale of 1 to 5, where 1 = not at all, 5 = always, 0 = do not know or do not want to answer) – 11 questions (Table 2).
- *UPTAKE*: To what extent do you think the following factors influence the further uptake of digitalization in agriculture? (Questions were rated on a scale of 1 to 5, where 1 = not at all influenced, 5 = entirely influenced and 0 = do not know or do not want to answer) – 17 questions (Table 3).
- *IMPACT*: To what extent do you think the digitalization of agriculture will affect the following areas? (Questions were rated on a scale of 1 to 5, where 1 = not at all affected, 5 = entirely affected, and 0 = do not know or do not want to answer) – 15 questions (Table 4).
- *PA*: Which factors do you think have the most significant influence on the uptake of precision farming in Hungary? (Questions were rated on a

scale of 1 to 5, where 1 = not at all influenced, 5 = strongly influenced, and 0 = do not know or do not want to answer) – 25 questions (Table 5).

Since the given blocks contain multiple answers, the list is not provided here, for simplicity. However, the given factors can be evaluated in the referenced tables.

Approximately 20 companies did not provide sales data, excluding them from the clustering analysis. Because of the missing observations, they were excluded from the clustering. While missing data imputation methods could offer reliable solutions, due to the sample size and variable nature, it was decided not to impute the missing data. Furthermore, gender, age, and education data were not used because, in some cases, the respondent was not the company's owner or key decision-maker. However, their answers were not excluded from the rest of the analysis. Finally, all six-level variables (0 and 1-5 rating) were converted to four levels, since Categories 1 and 2 and 4 and 5 contained only a few responses in some cases. In this way, we could reduce heterogeneity, but preserve the original meaning of these scales.

Results

Table 1 presents the descriptive statistics for the respondents. The companies were evenly distributed among the Hungarian regions, with a slightly higher share in the Northern Great Plain. Not surprisingly, most respondents were operating in agriculture, forestry, fishery, and mining, although other possibilities were also presented in the questionnaire. The median number of employees was 12, and the median sales were 235 million HUF. The employment levels ranged from companies with no employees to those with 1800 employees (mean = 84 employees). Similarly, sales varied significantly from 200 million to 5.7 billion HUF, with an average sales/employee ratio of 34 million HUF to 1 (Table 1).

In addition to the block questions, the $\log(\text{sales}/\text{employees})$ ratio and the sector indicators were included in the cluster formation. Figure 3 represents the three highest and lowest-rated answers among the block questions. For the first group (UPTAKE), respondents identified governmental support, a skilled and digitally competent workforce, and a digital infrastructure as the most significant factors in the spread of digitalization. These answers implied that agricultural stakeholders rated the facilitating

role of external factors highly. Notably, even the variables with the lowest ratings were not significantly behind those with the highest ratings. These variables included an appropriate marketing strategy, a more flexible legal environment, and the availability of additional funds beyond bank loans. The differences were more pronounced in the IMPACT and PA groups. Questions from the IMPACT group concerned the impact of digitalization on agriculture in specific areas. Respondents believed digitalization would primarily benefit those with IT skills, facilitate the spread of new production technologies, and provide a competitive edge to capital-intensive companies. The lowest-rated factors were concerned with enhancing the reputation of agriculture, improving the quality of rural life, and reducing social inequalities. The PA group examined the factors that influence the spread of precision farming in Hungary. According to respondents, increasing profitability, compatibility between technologies, and high investment costs were the main factors influencing the spread of PA. At the same time, the possibility of sharing assets, extra support for POs, and other factors were not perceived as significant (Figure 3).

The clustering algorithm has revealed a clear divide among the respondents, with each of the four blocks split into two clusters. The quality of the clusters was considered fair. The overall structure of the two clusters strongly implied a lack of adoption of these technologies. One cluster contained respondents who knew and possibly understood advanced technology, but never or rarely used it. In contrast, the other cluster contained respondents unaware of these technologies. This suggests that many of these technologies are not yet well-suited for agricultural production, and farmers lack critical information. The cluster details are listed below. The capitalized text refers to the names of the clusters, while the questions refer to their contents.

USE clusters — How often do you use the following digital technologies in your business?

The USE block was divided into two clusters: the First Cluster, comprising 39 companies (65%), and the Second Cluster, 21 companies (35%). The most notable difference between the two clusters was the use of advanced technologies, such as robotics and artificial intelligence. For the First Cluster, the use of advanced technologies was rare. The majority of respondents indicated that these technologies were not used at all or were used rarely

(with answers varying between 79.5% and 100.0%). However, many respondents were unaware of these technologies or their frequency of use within the company. Some technologies, such as social media and networks, banking and administrative services, cloud services (such as mobile applications), and websites, were used more frequently (Table 2). Czibere *et al.* (2023) reinforced these results by showing that, in some cases, Hungarian farmers were unaware of the benefits of precision agriculture technologies. The low level of education and inadequate skills further hindered the adoption of these technologies. Additionally, their lack of interest and commitment posed a problem. It is worth noting that other studies have also highlighted the importance of motivating farmers to use the technology (Balogh *et al.*, 2021).

UPTAKE clusters — To what extent do you think the following factors influence the further uptake of digitalization in agriculture?

In the UPTAKE sample, there were two clusters: 49 companies (81.7%) and 11 companies (18.3%). The first cluster perceived that most factors strongly influence the uptake of digitalization in agriculture, while the second cluster perceived no or weak effects of these factors. Both clusters agreed that the availability of a skilled and digitally competent workforce, governmental support, a suitable economic environment, secured equity capital, and data sharing might strongly impact the further uptake of digitalization in agriculture (Table 3). These results were supported by Czibere *et al.* (2023) and Balogh *et al.* (2021), who highlighted the importance of addressing the lack of skills and knowledge in the digital transition.

IMPACT cluster — To what extent do you think the digitalization of agriculture will affect the following areas?

Two clusters were formed, one with 33 companies (55.0%) and the other with 27 companies (45.0%). The clusters produced mixed results in terms of answers. The first cluster members expected that the digitalization of agriculture would affect or strongly affect youth participation in agriculture employment and the quality of life in rural areas and strengthen the position of Hungarian farmers at the international level. Conversely, members of the second cluster assumed the opposite. They also expressed neutral views on the impact of digitalization on sustainable agricultural produc-

tion, agricultural productivity growth, and the improved reputation of agriculture. Both clusters believed that agricultural digitalization would influence or strongly influence the promotion of a data-driven economy and contribute to the competitive advantages of capital-intensive businesses and those with IT skills. Both groups agreed that digitalization could facilitate the diffusion of new technologies. They also believed that it could significantly impact the exclusion of a less skilled workforce and increase the vulnerability of small producers to large producers. The first cluster did not express an opinion on whether social inequalities could be reduced. In contrast, the second cluster thought that the spread of digitalization would have little or no impact on it (Table 4).

PA cluster — Which factors do you think have the most significant influence on the uptake of precision farming in Hungary?

Two clusters were formed, with 49 companies (81.7%) and 11 companies (18.3%). The first cluster considered that virtually all factors affect or strongly affect the uptake of PA, while the second cluster reported heterogeneous responses. There was agreement regarding income support for farmers using the technology and increasing profitability. Both clusters identified that a lack of trust, expertise, and cooperation could have a considerable impact. Issues such as economies of scale, additional costs, inadequate financing schemes, high investment costs, and the current land tenure structure may also be contributing factors (Table 5). Czibere *et al.* (2023) also highlighted the lack of trust and cooperation in adopting precision agriculture technologies. Thus, the uptake of these technologies was more related to human capital than to the core areas of precision agriculture. Balogh *et al.* (2021) and Takácsné György *et al.* (2018) also highlighted the benefits of cheaper technology, including reduced investment costs, economies of scale, and a more supportive institutional background in Hungary.

Open questions were also provided for the respondents. Some noted that precision farming technology could not be adequately applied due to obsolete machinery, small farm size, and lack of collaboration. Others mentioned excessive administration and lack of knowledge on how to use data appropriately. One respondent raised the need to decouple market software from manufacturers. The high cost of technology, lack of skills, and absence of generational change were also mentioned. Respondents gave

varying answers when asked about their previous use of precision technology. The most common reason cited was that the technology did not meet expectations and did not result in significant yield increases or cost reductions. Furthermore, the labor input did not decrease significantly, and there were considerable issues with a lack of technical advice, expertise, skilled labor, and other technical problems. These issues were further complicated by underutilization due to farm size.

Respondents were asked to indicate their sources for obtaining information about precision agriculture ("Where did you learn about precision farming?"). Not surprisingly, the websites and printed journals were the most commonly used source of information. These sources are generally free, up-to-date, and cover highly specific agriculture-related topics. Technical and regular exhibitions were also important sources of information. Few farmers have heard about PA from expert advisers, from other farmers, or during related training. This finding was consistent with the clustering results, where producers expressed a need for broader technological advice, as the lack of expertise, technical know-how, and cooperation was a significant problem. Respondents were also asked to indicate the technologies most likely to shape the future of rural areas. The options 'Local or Remote Sensors' and 'Automated Systems' were the most frequently selected. This may be partly because these technologies are already used and may be seen as a competitive advantage. Expectations were high for data collected through remote sensing or increased drone use in Hungary. This may be related to the 'Data and Data Analysis' and 'Social media/Websites' options, as both increase data-driven decision-making differently. The less commonly chosen options were advanced technologies that fewer firms use or encounter in their operations (Figure 4). These results not only reinforce the findings of the literature but also demonstrate that successful deployment of the technology requires overcoming long-term challenges. Additionally, these results align with the general national issues of digitalization (Szenderák *et al.*, 2021). However, digitalization's exact ethical, social, political, cultural, and environmental impacts are still unclear, and further research is necessary (Lioutas *et al.*, 2021).

Discussion

Based on our results, policy mixes are necessary to target sustainability's economic, social, and environmental dimensions. Similar results were found in research analyzing successful climate policies. Stechemesser *et al.* (2024) found that out of 1500 policies between 1998 and 2022, only 63 were successful and achieved significant emission reductions. A key to these achievements was the presence of well-developed policy mixes. Similarly, we suggest the development of such policy mixes for Hungary since there was a strong duality in the digitalization trends that has to be targeted parallel. Other research also highlighted the importance of devising flexible policies (Ehlers *et al.*, 2022). In addition, the stakeholder network and the information flow also have to be targeted. There is an overwhelmingly large focus on the technological aspects of digitalization since the innovation process is a critical element of it. However, demand-side factors have also been addressed, such as social networks, information flows, habits, and practices (Creutzig *et al.*, 2018). This factor is crucial, since the cluster analysis highlighted the lack of information among the stakeholders. This requires a share of good practices and international results, as well as the demonstration of the effects of digital technologies. This would directly target the stakeholders of the second cluster, who lacked critical information.

Government support is indispensable for the technology to become widespread and part of everyday practices. Several obstacles highlighted by the respondents were related to profitability problems, the scale of economies, and investments. There is a risk that without the necessary intervention, the gap between large-scale and small-scale farms widens further. In addition, several benefits of large-scale digitalization are hardly measurable. For example, agriculture, especially animal husbandry, significantly drives biodiversity and habitat loss (Dasgupta, 2021; FAO, 2020). The lack of measurability, especially on a stakeholder level, may hinder farmers' environmental-related motivation (if they exist at all). In these cases, the presence of political regulations is essential. Even more so since it was apparent from the results that digitalization was viewed almost purely as a tool for increasing profitability. Social considerations were also present, especially regarding the workforce-related questions. However, the responses' environmental and rural-social dimensions were less pronounced. International tendencies were also similar. For example,

MacPherson *et al.* (2022) also highlight that although digital agriculture has received considerable attention for improving efficiency, productivity, and food security, less attention was paid to several principles of sustainable development, such as biodiversity conservation or human health.

Additionally, data-related questions will possibly require further regulations. Data privacy, access, and security are essential dimensions of digitalization (Garske *et al.*, 2021). Especially in the Hungarian agriculture and food industry, where cooperation is less pronounced, shared technology and data questions are especially important to address. Finally, several studies have highlighted the importance of flexible policies that address possible issues in advance (Ehlers *et al.*, 2021). The effect of digitalization is still uncertain, and policies must be adjusted to the rapidly evolving technology. However, certain aspects of agricultural policy, such as long-term land tenure policy, must be stable and foreseeable to create a solid foundation for further development.

Conclusions

Digitalization is transforming agriculture and the food industry in the European Union (EU) and Hungary, enhancing the sustainability and profitability of market players. However, digitalization also creates a digital divide for those without access to cutting-edge technologies. The agricultural sector is a strategic sector of the Hungarian national economy. However, it is highly vulnerable to climate change's potential impacts and faces competitiveness and efficiency problems. Digitalization is broadly regarded as a viable path towards a more economical and sustainable way of production. This study examined the use and adoption of novel technologies and how these technologies affect and impact rural areas.

The sample was observed to form two groups regarding the use of technologies. One cluster was aware of advanced technologies but chose not to utilize them, while the other cluster was often unaware of these technologies or unsure if they were being used. Social media, bank administration, cloud-based services (mobile apps), and websites were commonly used technologies. Regarding technology uptake, cluster formation was primarily influenced by perceptions of the impact of non-bank credit support, generational change, and stable, long-term land policy. Both clusters agreed that the impact of a skilled, digitally competent workforce, govern-

mental support, a suitable economic environment, and secured capital were significant factors in the uptake of digital technologies. Based on the respondents' feedback, the expansion of digitalization is anticipated to affect the formation of a data-driven economy, giving an advantage to companies with capital-intensive and skilled (primarily IT-related) employees.

Nevertheless, it will also promote the dissemination of new production technologies. Both clusters perceived the spread of technology as a threat to less skilled workers, which may lead to their exclusion from the labor market. Additionally, small farmers may become more vulnerable, as they find themselves at a competitive disadvantage compared to capital-intensive producers. Both groups agreed that the use of precision agriculture was primarily influenced by income and profitability factors, as well as a lack of confidence in the technology, a lack of experience, problems of economies of scale, the high cost of technology, inadequate financing schemes, and land tenure policies. These findings indicate that there could be significant barriers to the uptake of technological solutions despite their apparent benefits. The costs and advantages of the technology can be relatively well measured, which is not always the case for demand-side mitigation tools. As a result, technological solutions are much more prevalent and better understood than demand-side measures. However, our results suggest that policies should incentivize adopting and using these tools, because external factors were highly rated, and farm-level factors could hinder the adoption rate. The success of digitalization, particularly precision technology, relies heavily on external factors such as general digital competencies, profitability, and willingness to cooperate. These long-standing issues could significantly impact a successful digital transition in Hungary. A successful digitalization policy should boost profitability and offer a more sustainable way of production while considering the social dimension.

One limitation of the study is the moderate sample size, which resulted from a high level of non-responsiveness among industry stakeholders. This is a common issue in similar analyses, which could be attributed to the stakeholders' lack of information or understanding in these areas, as commonly mentioned in the responses. Furthermore, technological tools can be understood only in a broad context, as technology may manifest itself in various forms. This may make it difficult for stakeholders to fully grasp the differences between different tools, contributing to confusion in the field. However, our results were consistent with international literature. The

sample's heterogeneity in terms of company size, assets, and industry specifics may further complicate the analysis. Future research could benefit from focusing on the lack of understanding and incentives to adopt certain technologies. In addition to economic factors, the impact of technology on social and rural development issues may be worth considering in future research. Previous research addressed the implications of precision agricultural technologies without considering broader social issues, such as the lack of digital skills and incentives. A key question lies in the technological implications for skilled and non-skilled labor, especially in rural areas experiencing high unemployment and population decline.

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Compliance with ethical standards

This article does not contain any studies with human participants or animals performed by the authors. Extracting and inspecting publicly accessible files (scholarly sources) as evidence, before the research began no institutional ethics approval was required.

Data availability statement

All data generated or analyzed are included in the published article. The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation. The raw anonymized data can be provided by emailing the primary author.

Author contributions

All listed authors have made a substantial, direct and intellectual contribution to the work, and approved it for publication. The authors take full responsibility for the accuracy and the integrity of the source analysis.

Conflict of interest statement

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Annex

Table 1. Descriptive statistics of the sample

Variables	N = 81
Region	
Southern Great Plain	11 (14%)
Southern Transdanubia	10 (12%)
Northern Great Plain	22 (27%)
Northern Hungary	9 (11%)
Central Hungary	10 (12%)
Western Transdanubia	15 (19%)
Pest	4 (4.9%)
Sector	
Industry	1 (1.2%)
Research and Development	1 (1.2%)
Agriculture, forestry, fishery and mining	77 (95%)
Services	2 (2.5%)
Employment*	12 (4, 44)
Sales* (in million HUF)	235 (30, 939)
<i>Missing sales data</i>	17

Note: *Median and IQR.

Table 2. Two-step clustering with mixed variables (USE)

	First cluster	Second cluster	Importance
Size of cluster	39 (65.0%)	21 (35.0%)	
Blockchain or other certificate/traceability	Not at all or rarely (79.5%)	I do not know (57.1%)	1.00
Virtual reality/augmented reality	Not at all or rarely (94.9%)	I do not know (52.4%)	0.96
Autonomous systems and robotics (e.g., milking with robots)	Not at all or rarely (92.3%)	I do not know (38.1%)	0.84
Artificial intelligence to analyze data or guide action/decisions	Not at all or rarely (92.3%)	I do not know (47.6%)	0.71
3D printing	Not at all or rarely (100.0%)	Not at all or rarely (52.4,0%)	0.70

Table 2. Continued

	First cluster	Second cluster	Importance
Average of natural logarithm of Net sales/Number of Employees	15.95	17.28	0.25
Management Software (business management software)	Not at all or rarely (53.8%)	Often or always (33.3%)	0.22
Social media and social networks	Often or always (43.6%)	Often or always (81.0%)	0.22
Banking and administrative services	Often or always (79.5%)	Often or always (61.9%)	0.15
Profile	CP (48.7%)	CP (71.4%)	0.14
Sensors	Not at all or rarely (52.3%)	Often or always (57.1%)	0.13
Cloud services and applications (e.g., on mobile apps)	Often or always (46.2%)	Often or always (61.9%)	0.10
Websites, webshops, e-commerce	Often or always (53.8%)	Often or always (66.7%)	0.03

Note: Cluster quality = 0.2 (Fair) with N = 60 companies, CP = Crop Production.

Table 3. Two-step clustering with mixed variables (UPTAKE)

	First cluster	Second cluster	Importance
Size of cluster	49 (81.7%)	11 (18.3%)	
Available funds other than a bank loan	Affects or strongly affects (61.2%)	Has no or little effect (63.6%)	1.00
Generational change	Affects or strongly affects (75.5%)	Has no or little effect (45.5%)	0.95
Stable, long-term land policy	Affects or strongly affects (83.7%)	Has no or little effect (36.4%)	0.88
Predictable policy changes	Affects or strongly affects (83.7%)	Has no or little effect (36.4%)	0.77
A more suitable legal environment	Affects or strongly affects (73.5%)	Has no or little effect (54.5%)	0.76
Available digital infrastructure	Affects or strongly affects (83.7%)	Has no or little effect (36.4%)	0.73

Table 3. Two-step clustering with mixed variables (UPTAKE)

	First cluster	Second cluster	Importance
Predictable business relationships	Affects or strongly affects (77.6%)	Has no or little effect (54.5%)	0.64
Preferential bank loan	Affects or strongly affects (65.3%)	Has no or little effect (45.5%)	0.60
An appropriate marketing strategy	Affects or strongly affects (59.2%)	Has no or little effect (63.6%)	0.53
A skilled, digitally competent workforce	Affects or strongly affects (83.7%)	Affects or strongly affects (36.4%)	0.42
The available workforce, in general	Affects or strongly affects (73.5%)	Has no or little effect (54.5%)	0.37
A more flexible legal environment	Affects or strongly affects (61.2%)	Has no or little effect (45.5%)	0.34
Governmental support	Affects or strongly affects (81.6%)	Affects or strongly affects (54.5%)	0.32
Suitable economic environment	Affects or strongly affects (75.5%)	Affects or strongly affects (27.3%)	0.31
Workforce for basic tasks	Affects or strongly affects (71.4%)	Has no or little effect (45.5%)	0.26
Equity capital insured	Affects or strongly affects (71.4%)	Affects or strongly affects (36.4%)	0.25
Data Sharing	Affects or strongly affects (61.2%)	Affects or strongly affects (36.4%)	0.23
Profile	CP (51.0%)	CP (81.8%)	0.10
Average of natural logarithm of Net sales/Number of Employees	16.34	16.79	0.03

Note: Cluster quality = 0.3 (Fair) with N = 60 companies, CP = Crop Production.

Table 4. Two-step clustering with mixed variables (IMPACT)

	First cluster	Second cluster	Importance
Size of cluster	33 (55.0%)	27 (45.0%)	
Increasing the youth participation in agricultural employment	Affects or strongly affects (97.0%)	Has no or little effect (48.1%)	1.00
Improving the quality of life in rural areas	Affects or strongly affects (63.6%)	Has no or little effect (66.7%)	0.85
Strengthening Hungarian Farmers' position at the international level	Affects or strongly affects (75.8%)	Has no or little effect (51.9%)	0.75
Fostering sustainable agricultural production	Affects or strongly affects (75.8%)	Neutral (40.7%)	0.63
Agricultural productivity growth	Affects or strongly affects (84.8%)	Neutral (40.7%)	0.53
Enhancing the reputation of agriculture	Affects or strongly affects (66.7%)	Neutral (37.0%)	0.41
Facilitating a data-driven economy	Affects or strongly affects (84.8%)	Affects or strongly affects (40.7%)	0.36
Reducing social inequalities	Neutral (39.4%)	Has no or little effect (66.7%)	0.34
Competitive advantage for those with IT skills	Affects or strongly affects (93.9%)	Affects or strongly affects (63.0%)	0.22
Competitive advantage for capital-intensive companies	Affects or strongly affects (81.8%)	Affects or strongly affects (63.0%)	0.20
The spread of new production technologies	Affects or strongly affects (90.9%)	Affects or strongly affects (66.7%)	0.20

Table 4. Continued

	First cluster	Second cluster	Importance
Profile	CP (45.5%)	CP (70.4%)	0.11
The exclusion of small farms from the market	Neutral (39.4%)	Affects or strongly affects (55.6%)	0.10
The exclusion of less skilled workers	Affects or strongly affects (60.6%)	Affects or strongly affects (55.6%)	0.10
Average of natural logarithm of Net sales/Number of Employees	16.70	16.80	0.07
The vulnerability of small-scale producers is increasing	Affects or strongly affects (75.8%)	Affects or strongly affects (70.4%)	0.02

Note: Cluster quality = 0.2 (Fair) with N = 60 companies, CP = Crop Production.

Table 5. Two-step clustering with mixed variables (PA)

	First cluster	Second cluster	Importance
Size of cluster	49 (81.7%)	11 (18.3%)	
Access to advisory services	Affects or strongly affects (71.4%)	Has no or little effect (54.5%)	1.00
Specific training opportunities	Affects or strongly affects (69.4%)	Has no or little effect (54.5%)	0.95
Compatibility between technologies	Affects or strongly affects (87.8%)	Neutral (36.4%)	0.90
Lack of available technical advisory services	Affects or strongly affects (61.2%)	Has no or little effect (63.6%)	0.64
Improving workforce skills	Affects or strongly affects (81.6%)	Has no or little effect (36.4%)	0.64

Table 5. Continued

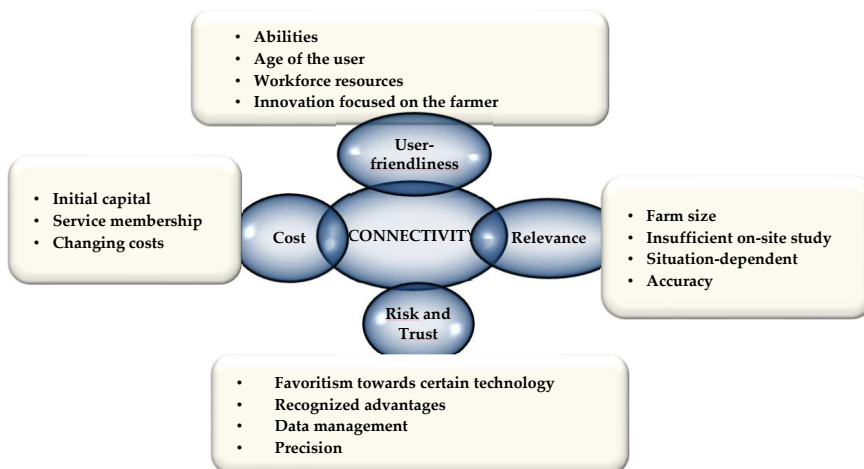
	First cluster	Second cluster	Importance
Lack of knowledge/expertise/information	Affects or strongly affects (71.4%)	Has no or little effect (45.5%)	0.57
Leasing option from agricultural integrator/external service provider	Affects or strongly affects (53.1%)	Has no or little effect (45.5%)	0.54
More efficient information flow	Affects or strongly affects (71.4%)	I do not know (36.4%)	0.52
The time required to introduce PA technology	Affects or strongly affects (57.1%)	I do not know (36.4%)	0.52
Income support for farmers using technology	Affects or strongly affects (87.8%)	Affects or strongly affects (36.4%)	0.49
Increasing profitability	Affects or strongly affects (85.7%)	Affects or strongly affects (54.4%)	0.46
Insufficient workforce skills	Affects or strongly affects (67.3%)	Has no or little effect (45.5%)	0.39
Preferential access to credit supporting PA Adoption	Affects or strongly affects (63.3%)	Neutral (36.4%)	0.35
Lack of trust in PA technology	Affects or strongly affects (57.1%)	Affects or strongly affects (36.4%)	0.28
Lack of experience to operate the technology properly	Affects or strongly affects (75.5%)	Affects or strongly affects (45.5%)	0.25
Lack of possible cooperation with other farmers	Affects or strongly affects (49.0%)	Has no or little effect (54.5%)	0.23
Problems of economies of scale	Affects or strongly affects (55.1%)	Affects or strongly affects (63.3%)	0.22

Table 5. Continued

	First cluster	Second cluster	Importance
Possibility of shared use of assets	Affects or strongly affects (42.9%)	Has no or little effect (36.4%)	0.20
Additional cost of operation	Affects or strongly affects (63.3%)	Affects or strongly affects (54.4%)	0.20
Inadequate support/financing scheme	Affects or strongly affects (67.3%)	Affects or strongly affects (45.5%)	0.13
Additional support for producer organizations	Affects or strongly affects (44.9%)	Has no or little effect (45.5%)	0.10
High cost of investment	Affects or strongly affects (73.5%)	Affects or strongly affects (54.4%)	0.10
Average of natural logarithm of Net sales/Number of Employees	16.57	15.76	0.07
Existing land tenure structure	Affects or strongly affects (49.0%)	Affects or strongly affects (36.4%)	0.06
Higher purchase price for farmers using the technology	Affects or strongly affects (71.4%)	Affects or strongly affects (45.5%)	0.06
Other factors	I do not know (57.1%)	I do not know (63.6%)	0.05
Profile	CP (59.2%)	CP (45.5%)	0.02

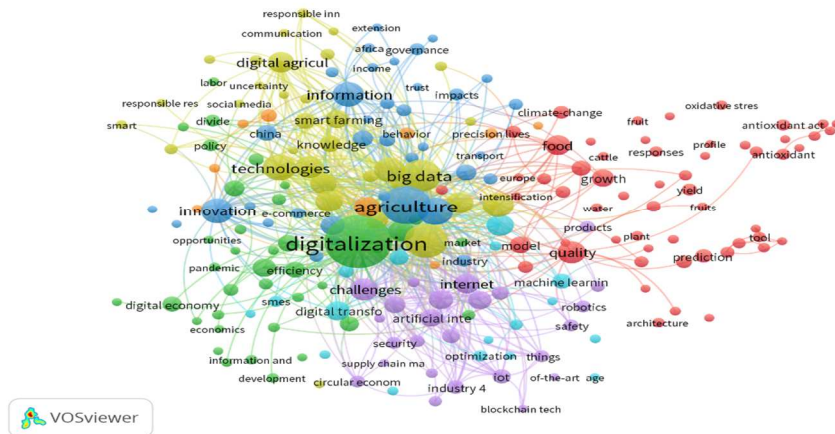
Note: Cluster quality = 0.2 (Fair) with N = 60 companies, CP = Crop Production.

Figure 2. Barriers to adaptation to digital tools in agriculture



Source: Authors' own editing based on McFadden *et al.* (2022).

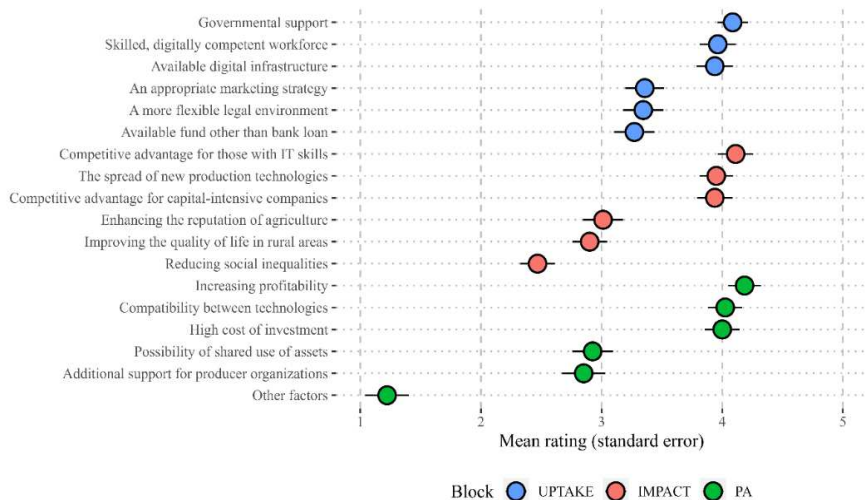
Figure 2. Co-occurrence network (author keywords) of the literature review



Note: The connection network was visualized using VOSviewer version 1.16.18, facilitating graphical representation. The settings were used at VOS as weights by occurrences; the keywords were clustered, which meant 7 clusters. The normalization method was made via association strength, the small clusters were merged, and values were used in layout, default attraction, and repulsion.

Source: Authors' own editing based on WOS data (2023)

Figure 3. The lowest and highest-rated variables among the block questions



Note: Only variables with predictor importance (PI) > 0.7 were included. USE: How often do you use the following digital technologies in your business? UPTAKE: To what extent do you think the following factors influence the further uptake of digitalization in agriculture? IMPACT: To what extent do you think the digitalization of agriculture will affect the following areas? PA: Which factors do you think have the most significant influence on the uptake of precision farming in Hungary? All questions were rated on a scale of 1 to 5.

Figure 4. Where did you learn about precision farming? (top) and Which technology do you believe will have the most significant impact on rural areas in the future? (bottom)

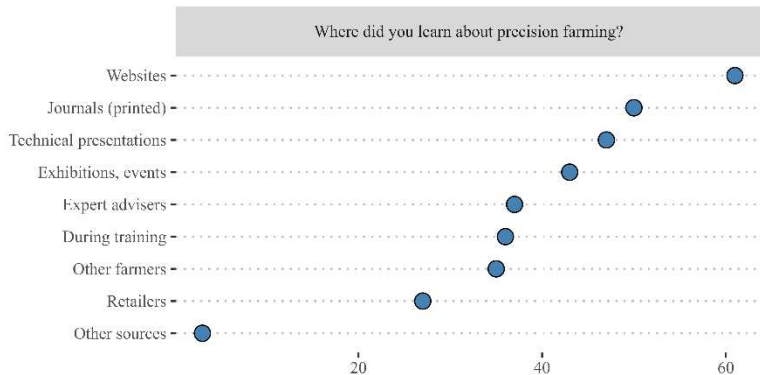
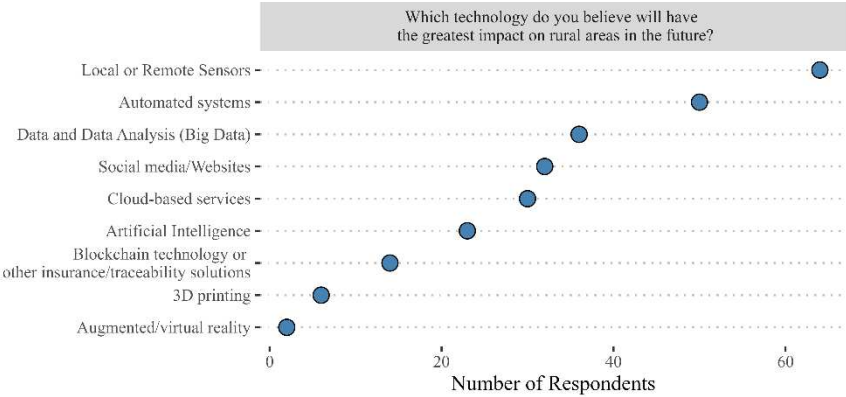


Figure 4. Continued



Note: Multiple selection questions.

Appendix

Questionnaire

In some cases, responses were paraphrased to simplify graphing or summarizing the clustering outcomes.

1. **How often do you use the following digital technologies in your business?** (Rate on a scale of 1-5, where 1 = not at all, while 5 = always, 0 = do not know)
 - a. social media and social networks
 - b. banking and administration services
 - c. websites, webshops, e-commerce
 - d. cloud services and applications (e.g., on mobile applications)
 - e. sensors (drone and satellite images for data collection).
 - f. blockchain or other certification/traceability
 - g. virtual reality/augmented reality
 - h. 3D printing
 - i. artificial intelligence (using artificial intelligence to analyze data or recommend action/decisions).
 - j. autonomous systems and robotics (e.g., milking robots)
 - k. management software (company management software)
2. **To what extent do you think the following factors influence the further uptake of digitalization in agriculture?** (Please mark your answer on a scale from 1 to 5, where 1 = does not influence at all, where 5 = ultimately influences, and 0 = cannot/does not want to answer)
 - a. Secured equity
 - b. The possibility of using state support
 - c. Discounted bank loan
 - d. Availability of other sources
 - e. Labor performing basic tasks
 - f. Skilled workforce (with digital competencies).
 - g. Available Workforce
 - h. The issue of farm transfer and succession (change of generations)
 - i. Data Sharing
 - j. A more flexible legal environment
 - k. A more appropriate legal environment
 - l. Adequate economic environment
 - m. Predictable policy
 - n. Stable, long-term property policy
 - o. A working, appropriate marketing strategy
 - p. Predictable business relationships, long-term contracts
 - q. Existence of digital infrastructure
3. **To what extent do you think the digitalization of agriculture will affect the following areas?** (Please mark your answer on a scale from 1 to 5, where 1 = does not influence at all, where 5 = ultimately influences, and 0 = cannot/does not want to answer)
 - a. The vulnerability of small producers to large farms is increasing
 - b. The spread of new production technologies
 - c. Reducing social inequalities
 - d. Promoting a data-based economy (more effective information collection and use)
 - e. Companies with substantial capital gain a competitive advantage
 - f. The less qualified workforce is pushed out of the primary sector even more
 - g. Gives a competitive advantage to those with IT skills (those with IT competencies gain a competitive advantage)
 - h. It has a positive effect on increasing the proportion of young people in agricultural employment

- i. The strengthening of Hungarian farmers at the international level
 - j. Improving the quality of life in rural areas
 - k. Expulsion of small farms from the market
 - l. Increase in agricultural productivity
 - m. Promotion of sustainable agricultural production
 - n. Increasing the reputation of agriculture
4. **Do you use any elements of precision plant-growing technology on your farm?**
- a. Yes
 - b. No
 - c. I used to, but I stopped
 - d. No, but I plan to introduce it
5. **Where did you learn about precision farming?**
- a. I have never heard of it.
 - b. Technical article/ professional magazine (printed)
 - c. Internet professional site
 - d. Specialist consultant
 - e. Exhibition/fair
 - f. During education
 - g. From another farmer
 - h. Trader
 - i. Professional presentation
 - j. Other
6. **Which factors do you think have the most significant influence on the uptake of precision farming in Hungary?** (Please mark your answer on a scale from 1 to 5, where 1 = does not influence at all, where 5 = ultimately influences, and 0 = cannot/does not want to answer)
- a. More efficient information flow
 - b. Increasing the skills of the workforce
 - c. Use of specialist consulting opportunities
 - d. Specific training opportunities
 - e. Existence of compatibility between technologies
 - f. Increasing profitability
 - g. Income replacement support for farmers using technology
 - h. Farmers using the technology would receive a higher purchase price
 - i. Possibility of shared equipment
 - j. Additional support for producer organizations (PO)
 - k. Rental option from agricultural integrator/external service provider
 - l. Discounted borrowing to support the introduction of PG
 - m. Incomplete availability of knowledge/expertise/information
 - n. High investment cost
 - o. Additional operating costs
 - p. The time required to introduce PG technology
 - q. Lack of experience required for proper operation
 - r. Distrust of the technology provided by PG
 - s. The inadequate support/financing system
 - t. Lack of available specialist advice
 - u. Inadequate workforce training
 - v. It does not match the size of the farm
 - w. The current ownership structure
 - x. Possible lack of cooperation/organization with other farmers
 - y. Other
7. **If you used precision technology before, why did you stop using it?**
- a. Lack of expertise/competence
 - b. Lack of skilled labor
 - c. Long payback period (or no payback)
 - d. Lack of professional advice
 - e. Technical difficulty

- f. The costs of individual work processes did not decrease significantly
 - g. The costs of individual input materials did not decrease significantly
 - h. The yield did not increase significantly
 - i. The working time expenditure did not decrease significantly
 - j. Advice/background support is inadequate
 - k. Underutilization due to plant size
 - l. I have not used it before
 - m. Other
8. **What do you think is the technology most likely to shape the future in rural areas?**
- a. Data and data analysis (Big Data)
 - b. Local and remote sensors (sensors, drones, etc.)
 - c. Artificial intelligence
 - d. Websites and online platforms
 - e. Blockchain technology or other assurance/traceability services
 - f. Social media
 - g. Cloud-based services
 - h. Automatic systems
 - i. Augmented/Virtual Reality
 - j. 3D printing
9. **Age**
10. **Gender**
- a. female
 - b. male
11. **Where is your farm located?**
- a. village/municipality
 - b. city
 - c. county seat
 - d. capital
 - e. other
12. **In which region is your farm located?**
- a. Western Transdanubia
 - b. Central Transdanubia
 - c. South Transdanubia
 - d. Northern Hungary
 - e. Northern Great Plain
 - f. Southern Great Plains
 - g. Budapest
 - h. Pest is going
13. **What is your highest education?**
- a. elementary or less
 - b. intermediate/technical school
 - c. university degree
 - d. other
14. **Do you have special qualifications in one of the following fields? (You can select more than one)**
- a. agriculture
 - b. food science
 - c. forestry
 - d. sustainability
 - e. digital technology (e.g., IT, electronics, etc.)
 - f. there is none
 - g. other

15. **What is the main profile of the economy?** (Main profile = where the given activity accounts for at least 66% of sales)
- crop production
 - horticulture
 - animal husbandry
 - mixed
 - other
16. **How would you describe your role in your current workplace?**
- owner (individual holding)
 - owner (economic organization)
 - manager but not the owner
 - manager and owner
 - agricultural consultant/ administrative worker
 - agricultural producer organization member
 - food value chain sector operator (logistics, retailers, etc.)
 - machine operator/maintenance (both plant and animal)
 - agronomist/plant doctor
 - accounting/payroll
 - IT or digital expert
 - researcher/ educational institute employee
 - service provider
 - no professional status
 - other
17. **In which sector do you work?**
- agriculture (forestry, fishing, mining)
 - industry
 - service
 - research and development
18. **Please state how many people worked at the farm according to the latest data!**
19. **Please enter the amount of your most recent net sales!**
20. **Please enter how much your last total balance was!**