The digitalisation of agriculture: Opportunities and drawbacks towards the reduction of GHG emissions in agriculture

STUDY

European Economic
and Social Committee

The digitalisation of agriculture

Opportunities and drawbacks towards the reduction of GHG emissions in agriculture

General information

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List of Abbreviations

AI	Artificial Intelligence
AKIS	Agricultural Knowledge and Innovation Systems
API	Application Programming Interface
ARIB	Agricultural Registers and Information Board
CAP	Common Agricultural Policy
CEADS	Common European Agricultural Data Space
CEF	Connecting Europe Facility
CO_2	Carbon Dioxide
EESC	European Economic and Social Committee
EIP-AGRI	agricultural European Innovation Partnership
EPRS	European Parliamentary Research Service
ERDF	European Regional Development Fund
EU	European Union
GDP	Gross Domestic Product
GDPR	General Data Protection Regulation
GHG	Greenhouse Gas
GIS	Geographical Information System
GPS	Global Positioning System
GVA	Gross Value Added
ICT	Information and Communication Technology
ID	Identification Document
IoT	Internet of Things
LoRaWAN	Long Range Wide Area Network
LSU	Livestock Unit
NRDP	National Rural Development Programme
OECD	Organisation for Economic Co-operation and Development
PERTE	Strategic Project for the Recovery and Economic Transformation
PLF	Precision Livestock Farming
RDI	Regulated Deification Irrigation
RoI	Return on Investment
UK	United Kingdom
US	United States
UUA	Utilised Agricultural Area
VRT	Variable Rate technology

Executive summary

Agriculture is a fundamental sector in the European Union (EU), contributing to food security, economic stability, and rural livelihoods. While agriculture is one of the sectors being affected by climate change the most, it contributes around 10% of the EU total greenhouse gas (GHG) emissions, mostly through the release of methane and nitrous oxide.

The application of digital technologies and tools in agriculture represents a significant advancement in the management of livestock and crop production, and simultaneously, can contribute to the reduction of the sector's GHG emissions. These technologies, ranging from precision farming tools, Internet of Things (IoT) devices, and remote sensing to artificial intelligence (AI) and big data analytics among others – enable data-driven decision-making aimed at optimising productivity, resource efficiency, and environmental sustainability. In livestock production, digital tools facilitate real-time monitoring of animal health, behaviour, and nutrition, while crop production benefits from field-specific input application, predictive modelling, and automated machinery. Collectively, these technologies contribute to the development of digital agriculture, enhancing food security and resilience in the face of climate change.

The study adopts a fact-based approach, relying on extensive secondary data collected through a structured literature review. Stakeholder interviews were conducted from Estonia, Romania, Germany and Spain to enrich and contextualise the findings of the literature review. According to analysis of the secondary data, three dimensions of sustainability were identified and established as guiding pillars. These pillars served as the framework through which the impacts of digitalisation were assessed in a coherent and structured manner, essentially addressing the targeted research questions.

Based on the literature review, **three pillars of a sustainable agriculture system were identified. These pillars are the environment, social and economic pillars that can be further distinguished to areas, where digitalisation has an impact**. The impacts of digitalisation on the **environment** can be demonstrated through **its impact on ecosystem services and on natural resources.** The former refers to the wider effects on the sector such as GHG emissions, while the latter refers to the use of soil, water and energy among others. The synergies between the use of digital technologies and ecosystem services offers a pathway to lowering the GHG emission of the agricultural sector. In crop production, the application of precision agricultural technologies reduces fuel consumption, the use of fertilisers and decreases the pesticide application, which directly translates into lowered emissions. In livestock production, the application of precision livestock farming technologies results in lowered GHG emission through improved animal health and feed conversion efficiency. Regarding the use of natural resources, the implementation of digital technologies serves as a backbone for data-driven decision-making enabling farmers to efficiently apply inputs, thus increasing resource-use efficiency.

The social impacts of digitalisation can be demonstrated through its effects on the **social capital and individuals** impact areas. The **former refers to the wider impacts on employment**, social cohesion and rural population, while the **latter refers to the individual needs** such as trainings and access to knowledge. **Digitalisation significantly contributes to the transformation of the rural labour markets**. Technologies, such as robotics and automated machinery substitute human labour, which leads to a net reduction of low- and unskilled agricultural jobs. At the same time, digitalisation increases the need for hybrid skillsets that combines analogue agricultural skills and knowledge with digital proficiency. Furthermore, digitalisation simultaneously creates new job opportunities in areas such as data analysis, technology maintenance, remote sensing and agri-software development. Conversely, it also drives a bifurcation of rural labour market, where highly skilled workers benefit from higher wages and better working conditions, while low-skilled labour faces job losses. Despite the negative effects, digitalisation holds considerable promise for attracting younger generations to farming, which can essentially lead to a cultural and generational change in the agricultural sector. **Individual-level effects are significant as well**. The adoption of digital tools depends on individual factors, such as age, education, experience and digital literacy among others. While the younger generation are more likely to adopt new technologies, the older generation are more conservative to adopt digital tools. Education and skills are key determining factors, as farmers with higher education or specialised trainings aiming at the use of digital tools are more likely to adopt technologies. Additionally, digitalisation calls for the upskilling and reskilling of agricultural workers, given the fact that those without such relevant skills are more exposed to the changes induced by the digital transformation of the sector.

The **economic impacts of digitalisation** in the sector can be showcased through **its impact on the organisations and on the market.** The impact on the organisation refers to the conditions affecting farmers on both the agricultural inputs and outputs alongside with their costs and benefits. The impacts on the market, however, refers to the agri-tech sector actors alongside with data ownership and data governance. The uptake of digitalisation heavily depends on the investment costs associated with adapting digital tools. The cost depends on the type of technology, and generally the more sophisticated tools pose greater financial burden on farmers, especially for smallholder who operate with tighter margins. In the absence of the economies of scale, the input savings and productivity gains offered by digital technologies enjoyed by smaller operations, result in a positive return on investment over a significantly longer time horizon. **Digitalisation of the agricultural sector carries significant technological, economic and policy risks associated with markets**. Technological risks associated with **data control, interoperability and innovation** can lead to having a handful of dominant agri-tech companies gain influence over both hardware and digital services, while farmers can be locked into closed ecosystems. The lack of interoperability can create data silos that limits flexibility and autonomy, while the centralisation of farm data under corporate platforms can compromise farmers' control over their own operational intelligence which combines their practical knowledge, decision-making abilities, adaptive skills and general know-how on their farm management. Market consolidation among the agri-tech service providers can pose negative impacts on affordability, equitable access and long-term competitiveness, as pricing may become increasingly concentrated. This allows dominant providers to impose higher costs for digital tools with limited pressure from competitors, essentially driving up the price of digital tools for farmers. The agricultural data governance remains uneven and fragmented across the EU. While regulatory instruments lay the basis for protecting personal data and enable trusted data sharing, several structural vulnerabilities remain. Agricultural data is often governed by the agri-tech companies, leading to an imbalance where farmers generate the data, yet they lack effective ownership over its use.

While the digitalisation of the sector carries some risks, it certainly presents tangible benefits to farmers as well. Based on the literature review, the application of digital tools (e.g. precision agriculture technologies) in crop production can increase yields by at least 10-15% and reduce fertiliser and pesticide use by 10-30%, in livestock production, more precisely in milk production, it can increase outputs by 10-15% and reduce food waste by 5-10% and energy use by 35%. In livestock, these gains are linked to the adoption of precision livestock farming technologies, including automated milking systems, sensor-based health monitoring and smart feeding technologies. The use of digital tools in horticulture increases yields as well, but the benefits are rather demonstrated in water savings (by 20-30%) and reduced fertiliser use (between 18-33%). Similarly, the digitalisation of irrigation systems leads to 20-40% water savings on average, yet higher savings can be achieved as well. These outcomes are largely enabled by smart irrigation systems, such as drip irrigation integrated with soil moisture sensors and climate forecasting tools allowing farmers to apply precise water quantity.

Contextual factors affect the uptake of digital technologies in the European Union Member States. The understanding of the contribution of such factors is key to sufficiently develop and promote measures to increase the use of digital technologies in the sector, and, at the same time as an end goal, reduce the GHG emissions of the sector. **Specific case studies on Estonia, Germany, Romania and Spain** highlighted main lessons when implementing digital solutions in the Member States. These case studies had special thematic areas to gather insights from different aspects of the contributing factors. The Estonian case discovered the enabling environment for the uptake of digital technologies, the German case study focused on the use of digital tools in organic production, the Romanian case study discovered the digital technologies in crop production in a smallholder heavy farm structure, whereas the Spanish case study discovered the use of digital technologies in irrigation. The main lessons learned from the case studies are the following:

Estonia:

- **Creating a strong e-government system can help more people, including farmers, use digital tools and build their digital skills and trust in technology.**
- **Digitalisation and "once-only" principle** significantly reduce bureaucracy and ease the administrative burdens as well as increase the speed of proceedings by integrating different databases across governmental actors to avoid data entry duplications by ensuring that users have to provide certain type of standard information to the authorities "once-only". This results in time savings for farmers and faster application proceedings.
- **Clear rules on data ownership and access** are essential to increase trust and to keep farmers in charge of their data.

Romania:

- **Farm structure matters immensely for digital uptake**, among other factors such as age of farmers, level of education. The rural development and agriculture support programmes and supporting schemes must be tailored for their specific needs as well.
- **The high-level political recognition and dedication to digitalisation is essential** to boost the uptake of digital technologies. A dedicated strategy on the digitalisation of agriculture supports the alignment of future support schemes (such as CAP) to shape the digital landscape of the agricultural sector.

Germany:

- **Economic, environmental and social benefits go hand in hand**. Organic farming has expanded significantly in Germany, and the application of digital tools and solutions can, on the one hand, increase yields while saving agricultural inputs; and on the other hand, support the farmers post-harvest in a form of increased traceability, e-commerce and marketing. The application of digital tools also can allow farmers and agricultural workers to engage in different types of tasks such as remote monitoring, which can ease the workload of farmers, increase working conditions, and can attract younger generations to the agricultural sector.
- **Digitalisation should be the mean and not the goal**, as the use of digital tools will not automatically lead to better environmental results. However, utilising digital tools in a smart and efficient manner can reduce the GHG emissions, and support farmers to sustain organic production.

Spain:

- **The combination of high-level political commitment, public investments and policy support** has been catalytic for digitising Spain's irrigation systems. The infusion of national and EU funds, and the public-private partnerships are essential to generate the most impact possible.
- **One solution does not fit all, so there is a need for a holistic and context-specific approach:** digital transformation in agriculture is uneven. This entails that one-size fits all approach does not work in case of digitalising the agricultural sector.
- **Demonstrating hands-on benefits for farmers significantly benefits the adoption rate of digital technologies** among farmers, even among those, who were sceptical of digital solutions. Demonstrative plots and actual success examples can convince farmers to adopt digital technologies.

Building upon the findings of the assessment of the environmental, social and economic pillars of sustainability, as well as the country-specific case studies that provided contextual insights the following recommendations were developed. Furthermore, the recommendations are expected to deliver tangible results when efficiently implemented. The table below demonstrates how the recommendations can contribute to a more integrated and balanced approach to digitalisation in the agricultural sector.

Table 1: The potential effects of the recommendations on the pillars of sustainability

Nr.	Recommendation	Potential effects on the pillars of sustainability		
		Environmental	Social	Economic
I.	**Establish and strengthen a dual investment approach targeting rural digital infrastructure.**	The increase in uptake of digital technologies in agriculture can lower GHG emission.	Ensures fair and equal access to digital tools and network in rural areas. The use of digital tools can make the agricultural sector more appealing for women and young people as well.	Increases efficiency of the agricultural sector by introducing digital tools.
II.	**Combine and promote synergistic investment incentives in digital technologies and renewable energy systems.**	Contributes to reducing the GHG emission of the agricultural sector via renewable energy generation.		Increases competitiveness and resilience of the agricultural sector.
III.	**Design and strengthen tailored incentives schemes for smallholder farmers and young farmers to enable equal access to digital and green innovations.**	Contributes to reducing GHG emission of the agricultural sector, and positively influences the biodiversity.	Ensures fair and equal access to agricultural subsidies and grants, ensuring fair opportunities to invest in technology.	Increases competitiveness and resilience of smallholders. Increases food security due to increased productivity, especially in the local context.
IV.	**Tailor, strengthen and promote trainings, advisory support and digital capacity building activities for rural innovations.**	Increases environmental awareness by farmers.	Ensures fair and equal access to knowledge, lowering the digital skill gaps and ensures the reskilling / upskilling of rural workforce.	Increases competitiveness of rural workforce.
V.	**Establish robust data governance frameworks to protect farmers' rights and ensure fair and transparent use of agricultural data.**		Increases trust in digital solutions among farmers and other stakeholders.	Ensures farmers' ownership over their data, and avoids vendor lock-ins.
VI.	**Leverage agricultural data to strengthen CAP cross-compliance and quantify the environmental and economic impacts of digital agriculture measures**.	Contributes to assess the impact of digitalisation on the environment (e.g. GHG emission, soil health).	Clear and transparent communication of the quantified environmental benefits can positively change the perception of agriculture among young people.	Contributes to assess the impact of digitalisation on economic (e.g. yields, input usage etc.).
VII.	**Promote open-source platforms and farmer-led data infrastructure to safeguard data sovereignty and prevent agricultural-data monopolies.**	Enhanced platform access can result in more accurate datasets, thus inspiring more environmentally appropriate decision-making and actions.	Increased trust in digital technology platforms among farmers. Limits data sovereignty- and transparency concerns.	Enhanced levels of digital technology uptake, especially among smaller farms, inspiring an increase in digital investment and productivity. Limits economic risks posed by agri-data monopolies.

Source: KPMG (2025).

1. Introduction

1.1 Background

The study on "The digitalisation of agriculture: opportunities and drawbacks towards the reduction of GHG emission in agriculture" was commissioned by the European Parliament Research Service (EPRS) for the European Economic and Social Committee (EESC). The study is carried out by KPMG Advisory Ltd. (KPMG) as project leader together with the Corvinus University of Budapest (Corvinus). The formal kick-off meeting was held on the 9th of April 2025 between EPRS, EESC, KPMG and Corvinus which marked the start date for the deliverables.

1.2 Context

Agriculture is a fundamental sector in the European Union (EU), contributing to food security, economic stability, and rural livelihoods. The agricultural landscape of the EU is highly diverse, ranging from small-scale farmers to large-scale, industrial farms. The sector remains a key driver of rural development and employment, but it also faces significant challenges related to environmental degradation, climate change and depopulation of rural areas.

While agriculture is one of the sectors being affected by climate change the most, it contributes around 10% of the EU total greenhouse gas (GHG) emission[1] mostly through the release of methane and nitrous oxide. Traditional agricultural methods have encouraged the heavy use of agrochemicals, high consumption of fossil fuel energy as well as monoculture production leading to soil degradation, have polluted water systems and damaged biodiversity. In line with the climate neutrality aims of the EU by 2050, agriculture must reduce emissions, where digital farming and especially precision agriculture, an important family of digital technologies in agriculture, can play an important role.

The application of digital technologies and tools in agriculture represents a significant advancement in the management of livestock and crop production. These technologies, ranging from precision farming tools, Internet of Things (IoT) devices, and remote sensing to artificial intelligence (AI) and big data analytics among others – enable a data-driven decision-making aimed at optimising productivity, resource efficiency, and environmental sustainability. In livestock production, digital tools facilitate real-time monitoring of animal health, behaviour, and nutrition, while crop production benefits from field-specific input application, predictive modelling, and automated machinery. Collectively, these technologies contribute to the development of digital agriculture, enhancing food security and resilience in the face of climate change.

Table 2: The main types of technologies utilised in crop production and livestock production[*]

Technology	Crop production	Livestock
Precision farming tools	Global Positioning System (GPS) and Geographical Information System (GIS), Variable Rate technology (VRT)	Feed optimisation systems, automated milking systems
Internet of Things (IoT)	Sensors, weather stations	Smart collars, health monitors, sensors (incl. biosensors)
Drones and Aerial Imaging	Crop health monitoring, pest detection, spraying and mapping	Herd monitoring, pasture analysis
Robotics and automation	Autonomous tractors, robotic weeders and harvesters	Robotic milking, automated cleaning systems

[1] European Commission (2023): Study on options for mitigating climate change in agriculture by putting a price on emissions and rewarding carbon farming. Accessed at link.

[*] The technologies in the crop production and livestock production sectors will be analysed to a varying depth to provide an overall overview of the state of play of digitalisation in the European agriculture.

Big Data and Analytics	Yield mapping, soil analytics, input optimisation	Performance tracking, feed efficiency analysis
Satellite imagery	Field mapping, crop production, early stress detection	Grazing management
Blockchain technology	Supply chain transparency, certifications	Traceability, supply chain transparency
Software applications	Farm management solutions (incl. decision support systems)	Farm management solutions (incl. decision support systems)

Source: KPMG (2025).

While utilising digital technologies, including precision agriculture in farming can bring significant benefits, they can also create significant burden on farmers, especially on small-scale farms, essentially leading to a two-speed EU farming system. The high costs of digitalisation generally favour large farms, while the uptake of digital technologies in farming can have implications on the social cohesion of rural areas. On the one hand, the depopulation of rural areas can lead to the scarcity of agricultural workers, hence digital technologies and solutions can help farmers overcome labour shortage[2]. On the other hand, however, the spread of digitalisation in traditional sectors such as agriculture, which serves as significant source of employment in Europe[3], can lead to narrowed job opportunities for the rural population.

Data privacy and data security are further concerns. The use of digital technologies in agriculture relies on data collection from various sources (such as drones, sensors, and satellites). This sensitive data may include details about crop yields, soil conditions, farm operations and personal information about farmers. This entails that data privacy and data security concerns present a significant challenge in precision farming and raise critical questions regarding data ownership and fair use of data. To address this issue, so far, the EU, through its European Strategy for Data, introduced Common European Agricultural Data Space (CEADS) to facilitate sharing agricultural data between private actors (such as farmers, data service providers) and public authorities[4], and published a Code of Conduct[5] on agricultural data sharing to advise stakeholders on the main principles related to rights and obligations of using and sharing data.

1.3 Scope and objectives

Following the definition of deliverables in the framework contract[6], the output of this assignment is to be understood as a study, which offers a more detailed view on a particular subject, including a wider array of methodologies applied in order to formulate clear and concise findings, conclusions, and recommendations.

The primary objective of this study is to assess the impact of digitalisation on EU agriculture by analysing available technologies, investment costs, and user profiles along six specific objectives.

- **Objective 1**: Provide an overview of current data related to digitalisation in agriculture
- **Objective 2**: Assess the implications of digitalisation on GHG emissions and the future of EU farming (inter alia on the basis of selected case studies)

[2] For example link.

[3] Agriculture accounted for 4.2% of total employment in 2020 in the European Union according to Eurostat: Employment in agriculture, forestry and fishing, 2020. Data accessed at link.

[4] The "*AgriDataSpace*" which served as a preparatory action for CEADS concluded its activities in 2024. The follow-up actions regarding CEADS are expected to continue in 2025. For further information, please refer to this link.

[5] For further information, please refer to the EU Code of Conduct on agricultural data sharing by contractual agreement publication. Accessed at link.

[6] External Expertise for Ex-ante Impact Assessment, Ex-post Evaluation, Estimating European Added Value, Research Focused on Organised Civil Society and Stress-Testing of EU Policy. Reference nr.: EPRS/DIRB/SER/23/016, Lot 7: Regional development, agriculture and fisheries.

- **Objective 3**: Assess opportunities for digital transformation in farming
- **Objective 4**: Assess inclusivity in agricultural digitalisation
- **Objective 5**: Recommend strategies to support rural employment and community resilience in the context of agricultural digitalisation, assessing potential changes in job demand and opportunities for job creation
- **Objective 6**: Analyse the current use of data, risks of corporate consolidation in the precision farming sector and data monopolisation in precision agriculture

2. Methodology

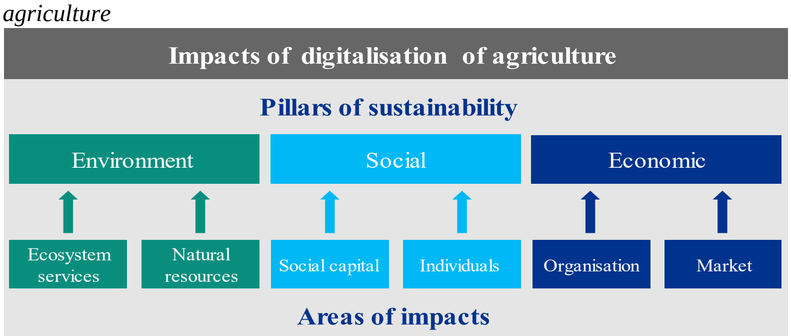
Primary data collection consists of three of interviews with different stakeholders from the agricultural sector focusing on digitalisation of agriculture from farmers' perspectives, complementing information that is already available in secondary sources. The interviews have a double focus: 1) gather and collect existing data on digital agriculture in Europe and ensure that the data collection activities are thorough; and 2) gather information and perspectives on digital agriculture from stakeholders involved in agricultural production for the case studies. During the inception phase, three interviews were conducted to better shape the scope of the study with stakeholders from EESC, while a total of seven stakeholder interviews were conducted from Estonia (2), Romania (2), Germany (2) and Spain (1) to better contextualise the findings of the literature review.

Secondary data collection is the main source of information for the assessment. In respect to this, we relied on a wide range of data repositories to gather statistical and qualitative data. Information and data accessed through our academic network e.g. academic resources will be complemented with data steaming from datasets such as Refinitiv Eikon. Furthermore, we relied on publicly available datasets such as Eurostat. A final list of relevant databases is listed in Annex 2, which have been reviewed and synthesised throughout the process of composing this report.

3. Assessment of environmental, social and economic impacts

The assessment concentrates on the three pillars of sustainability. To demonstrate the impacts generated by digitalisation of agriculture on different pillars of sustainability, the findings of the assessment are demonstrated by the areas of impacts.

Figure 1: Pillars of sustainability and areas of impacts of digitalisation in agriculture



Source: KPMG (2025).

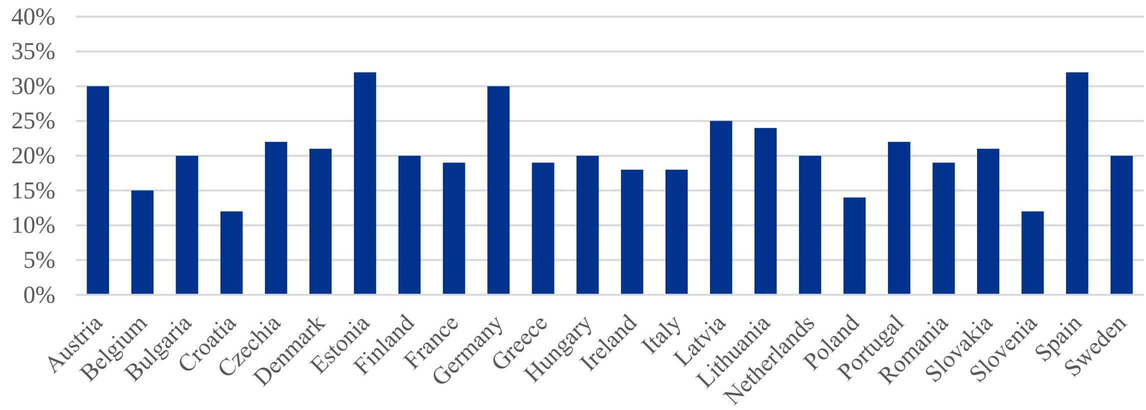
Under the environmental pillar we established two areas of impacts. Based on the literature review, **these areas are ecosystem services and natural resources**. The findings are demonstrated through these elements to be able to conduct a structured analysis of the findings of the literature review. Ecosystem services refer to the wider effects of digitalisation on the environment, such as GHG emissions and preservation of biodiversity, while natural resources refer to the use of soil, water and energy among others. **We identified two areas of impacts under the social pillar. The findings are demonstrated through social capital and individuals.** The social capital refers to the wider impacts on employment, social cohesion and rural population, while individuals refer to the individual needs, such as training needs, access to knowledge and upskilling opportunities. **As for the economic pillar, we established the organisation and market areas**, whereas the impact on organisations refer to conditions affecting farmers on both the agricultural inputs and outputs alongside with their financial costs and benefits. The impact on the market refers to the agri-tech sector actors alongside with data ownership and data governance. The relationship between the research questions and the chapters is presented in Annex I. This annex provides a structured overview of how each question is addressed throughout the report.

3.1 Characteristics of farms utilising digital technologies in agriculture

The adoption of digital technologies varies between farm location, sizes, sectors, financial capacity and demographics across Europe. The use of digital tools on farms has expanded in recent years. By the early 2020s, roughly one-fifth of EU farms had made some investments in digital farming solutions (e.g. precision farming equipment, software) in the prior years, according to the EU survey conducted in 2023[7]. In a survey conducted between 2021 and 2022[8], 48% of the surveyed farmers reported that they use at least one smart farming technology, with an additional 37% planning to use smart farming technology in the future. Only 15% of the farmers said that they do not foresee utilising such technologies in the future.

Digital divide is a prominent trend in digitalisation in agriculture across the European Union**. Northern and Western European countries have higher adoption rates of digital farming technologies, while Southern and Eastern countries in general lag behind on average**. This reflects underlying differences in farm structures, incomes, and infrastructure across the Union. The average adoption rate among Western European farmers is about three times higher than that of Eastern European farmers (41% vs. 13% on average), according to a survey conducted in early 2020s[9]. Similarly, over half of the farms in Western Europe (56%) have adopted digital farm management software compared to only 6% in Eastern Europe. This divide underscores that while digital farming is progressing in the EU, it is concentrated segmentally. There are, however, exceptions to this trend. The survey[10] demonstrates that the highest adoption rate can be found in Estonia (32%), a country considered as Eastern Europe, and in Spain (32%) considered as a country of Southern Europe, while the EU24 average was 20%. The share of farms that have invested in digital solutions and / or advanced machinery to optimise the use of fertilisers or crop protection products are demonstrated below.

Figure 2: The share of farms that had invested in digital solutions and / or advanced machinery to optimise the use of fertilisers or crop production products, 2022



Source: European Commission – European Investment Bank 2023. KPMG's design.

[7] European Commission – European Investment Bank (2023): Survey on financial needs and access to finance of EU agricultural enterprises.

[8] According to the online survey from 46 different counries with a total of 484 responses. For further information, please refer tot he website of Demeter at link.

[9] World Economic Forum (2022): Transforming Food Systems with Farmers: A Pathway for the EU. Accessed at link.

[10] European Commission – European Investment Bank (2023): Survey on financial needs and access to finance of EU agriculture enterprises.

Farm size is one of the clearest determinants of digital technology uptake. Larger farms are markedly more likely to invest in and deploy digital tools, whereas smallholders often lag behind due to the differences in both capacities to invest and perceived returns from technology. Only around 3% of holdings are above 100 hectares in the EU[11], yet these farms account for a disproportionate share of production and technology use. The literatures show that larger enterprises prioritise digitalisation in their investment decisions for more than smaller farms. With greater land and herd sizes, large farms can spread the cost of expensive technologies over more output, improving their cost-benefit equitation. **Smaller farms, which make up the majority of EU holdings, have comparatively low adoption rate of digital tools**. Many small farmers continue to rely on traditional knowledge and basic machinery, with limited integration of high-tech solutions. As of 2020, more than 72% of farmers were still relying on practical experience, without any specific agricultural education[12] or formal agricultural training, demonstrating a knowledge gap that can hinder the uptake of digital tools in agricultural practices. Cost remains the primary barrier to adopting digital technologies for smallholders. Around 53% of farmers said that most smart farming technologies are simply too costly to adopt[13]. Small farmers are more likely to have tight profit margins hence investing in digital technologies may be more challenging to justify. As a result, only a minority of smallholder farms currently use digital innovation tools, and those tend to use simpler solutions (such as smartphone apps, or basic sensors). According to the literature, smallholders tend to focus their limited investment capacity on essentials (such as irrigation or working capital), while larger farms channel more investment into digital solutions.

The uptake of digital tools varies by agricultural sectors as well. While both crop producers and livestock farmers use digital tool innovations, the uptake shows differences. **The arable sector has been a major focus of precision agriculture technologies in Europe**. Large arable farms have widely adopted GPS-based guidance and mapping (e.g. yield monitors and GPS auto-steer systems). The application of VRTs have been increasing, however, often limited to bigger enterprises or farms in pilot programmes. According to the literature review, in some Western EU countries 20-40% of farms have adopted at least basic precision farming tools, whereas more advanced practices (such as fully automated VRTs) have had a lower uptake (15% on average). Within the crop sector, high-value horticulture stands out. Greenhouse and intensive horticulture producers in some countries (e.g. the Netherlands, Belgium or Spain) often use cutting-edge climate control systems, hydroponic sensors, and AI-driven monitoring to optimise agricultural outputs. Horticulture accounts for almost one-fifth of the total value of agricultural production in the EU, and many larger greenhouse operations are at the forefront of digital farming. The digital divide is visible in the segment as well. Smaller, open-field vegetable or fruit production (commonly in Southern Europe) have more limited tech adoption, compared to those in the Netherlands, Belgium or Spain. **The livestock sector shows a mixed picture. Dairy farming has been a leader in adoption automation and sensor technologies, while other segments show slower adoption rate**. The European dairy farmers, particularly those with larger herds, have invested in tools such as automated milking systems, sensor-based heat and health monitors, and precision feeding systems. Northern European countries (e.g. Denmark, Netherlands and Germany) have widespread adoption of digital technologies in dairy farming. Studies indicate that dairy farmers in Europe are more likely to adopt technologies than other farmers in animal husbandry, especially as herd sizes and labour costs increase. In contrast, sectors like beef cattle, sheep, and small-scale mixed livestock have been witnessing a slower adoption rate. These operations often have lower profit margins and less incentives to invest in costly monitoring equipment. Pig and poultry farms tend to use automation (e.g. climate control or automated feeders) as standard, but these are often considered as conventional technologies

[11] According to Eurostat (2020): Farm indicators by legal status of the holding, utilised agricultural area, type and economic size of the farm and NUTS 2 region.

[12] CEJA (2023): Smart farmers for smart farming. Policy paper.

[13] According to DEMETER: The Farmer’s Voice survey. For further information please refer to link.

now. Newer digital innovations (like AI for health detection or IoT sensors for individual animal tracking) are emerging mostly on experimental farms or large-scale units.

The demographic profile of farmers plays a significant role in technology adoption as well. Key factors include age, education level, and whether a succession plan is in place for the farm. In general, younger farm operators are significantly more likely to adopt digital tools[14]. The older generation of farmers are more hesitant, and in a way more conservative, to adopt digital tools. Education and skills are another key element to adopt digital tools. Farmers with high education or specialised trainings are more likely to adopt digital technologies, while farmers without formal education are more conservative in adopting new technologies in their operations. Furthermore, the training level of agricultural workers determine the efficiency of digital technologies. The literature highlights the need for trained agricultural workers to maintain and operate the digital tools (e.g. sensors) and to interpret the generated data to make informed decision. In the absence of such skills, the return on such investments may be hindered, which may disincentivise farmers from further investments in advanced technologies in the future.

Digital skills and knowledge need for farmers and agricultural workers

Based on the review of the collected materials, the lack of digital skills and knowledge is one of the key barriers of adopting digital technology. This effects not only the farmers, but the agricultural workers as well. The rural population engaged in agricultural production can be at a disadvantage if the required skillsets are missing.

In general, digitalisation is an enabler that requires a new set of competencies, that are not only technical but also organisational and strategic. Based on the review of the relevant literature, the following areas were identified where trainings and knowledge-sharing could benefit farmers and agricultural workers:

- **Digital literacy and technical knowledge** are essential. Many agricultural workers (incl. farmers and farm managers) lack the foundational skills to operate and manage digital tools. This skill gap is particularly pronounced among older farmers, marginalised communities and those in rural areas with limited educational opportunities.
- **Data management and analytical skills** are among the most cited skillsets. Digital farming technologies often generate large volumes of data, and agricultural workers must learn how to interpret this data and make informed decision.
- **Organisational capacity** is required additionally to technical skills. Farmers and agricultural workers need competencies to align their operations with digital tools. This includes the understanding of how digital technologies integrate into their every-day work, into the supply chain, how those affect cost structures of the farm, and how they may open new market opportunities.

The ability to finance new technology is a decisive factor in whether a farmer adopts digital tools. **Financial capacity, access to capital, credit and subsidies, strongly influences adoption rate**. Farmers who adopted digital technologies in the past years often share certain financial advantages. Generally, the more profitable farms invest in digital technologies. Higher income of farms, that are often correlated with larger scale or high-value production, means more ability to absorb risk and long payback periods that comes with the implementation of new technologies. Financially strained farms are less likely to tie up capital in uncertain tech. Furthermore, there is a psychological aspect as well. Farmers who are comfortable with their financial position are more willing to experiment, whereas those under financial stress avoid additional expenditures. Many farmers view technology as a long-term investment in efficiency, which they can prioritise only once basic economic outcomes are achieved. Furthermore, the farms' economic status also determines their success of obtaining loans. A recent

[14] According to a survey conducted by the World Economic Forum, the likeliness of digital tool adoption is five times higher among farmers under the age of 35 than farmers above 55 years old.

survey[15] shows that larger enterprises are more confident in approaching banks and had higher loan approval rates, whereas small farms had more unsuccessful loan applications and often did not even apply due to fear of rejection. This entails that larger farms can leverage loans or leases to invest in technology, while smaller farms mostly have to rely on their own capital.

According to the analysis of the collected literature, several promising digital solutions are identified that contribute significantly to both sustainability and productivity in agriculture. These technologies range from data-gathering tools, automated systems to decision-support platforms. These digital technologies have transformative potential for EU agriculture by promoting efficient resource use, reducing environmental externalities, and increasing resilience and resistance. The most promising solutions combine AI, IoT, robotics, blockchain, and integrated platforms, offering actionable insights, automating processes, and enhanced transparency across the agri-food system.

Table 3: Most promising digital solutions, based on the collected literature

Digital solutions	Key features	Sustainability impact
Precision Agriculture Technologies	Remote sensing, GPS, variable-rate technology, smart irrigation	Reduces input usage and waste, improves resource efficiency
Artificial Intelligence and IoT	AI-driven prediction, IoT sensors, cloud computing	Optimises input use, enhances forecasting, lowers environmental load
Decision-Support Platform	Platforms providing real-time advice, decision-making and efficient management	Optimise input use
Robotics and Automation	Robotic weeders, autonomous sprayers, robotic milking systems	Reduces chemical usage and labour, improves animal welfare
Blockchain for transparency	Traceability, quality, monitoring and carbon tracking tools	Ensures ethical supply chains
Mobile-Based Advisory Tools	Apps providing crop management and market access information	Empowers smallholders with low-cost digital access

Source: KPMG (2025).

3.2 Environmental impacts of digitalisation of agriculture

3.2.1 Ecosystem services

Ecosystem services such as pollination, nutrient cycling, soil formation and carbon sequestration are fundamental to sustainable agriculture. When managed properly, these services enhance productivity while naturally mitigating greenhouse gas (GHG) emission by storing carbon in soil and vegetation and reducing reliance on synthetic inputs. Optimising these services at scale requires precise, timely and location-specific information. Digital tools, such as remote sensing, IoT sensors and AI-driven platforms enable farmers to monitor ecosystem functions, apply inputs efficiently, and adopt practices like precision farming or regenerative agriculture. Ultimately the synergy between ecosystem services and digital agriculture offers a pathway to lowering the GHG emissions of the agricultural sector. The agricultural sector accounts for about 10% of EU greenhouse gas (GHG) emissions, with methane from livestock and nitrous oxide from soils being the largest sources[16].

Digitalisation is increasingly recognised as a transformative force in agriculture, not only for improving productivity and economic viability, but also for contributing to environmental sustainability. One of the most significant environmental benefits associated with digital agriculture is its potential to reduce

[15] Ibid.

[16] EEA (2024): Greenhouse gas emissions from agriculture in Europe. Accessed at link.

GHG emissions. Based on the review of the collected publications[17], there is consistent evidence that digital technologies can help lowering emission, though the extent and nature of the reduction vary by technology, field of application and context[18].

At the forefront of this impact are precision livestock farming (PLF) technologies, which have shown a clear reduction in emission intensity. A study on average Scottish dairy farms presented **that PLF tools such as oestrus detection sensors and health monitoring systems resulted in up to 6-7% reduction in GHG** emission per unit of milk. While total **farm emissions declined more modesty (by around 1.4% to 2.5%)**, the efficiency gains per unit of production were substantial. Similarly, in Scottish beef farms, **PLF tools contributed to up to 6.8% reduction in total GHG emissions** and up to **12% reduction in emission intensity**, mainly through improved animal health and feed conversion efficiency.

These findings are corroborated by several studies that model GHG savings from adoption of smart feeding systems, precision health monitoring systems, and weight-tracking technologies utilised in livestock production. The core mechanism lies in reducing waste and losses through real-time decision-making and predictive monitoring, which leads to reduced inputs per unit of output.

Digitalisation in crop production has evident benefits in terms of GHG emissions as well. Precision agriculture technologies, such as GPD-guided machinery, variable rate fertiliser applications, automated irrigation systems, and networks of sensors, help to reduce the overapplication of agricultural inputs such as fertilisers, a major source of nitrous oxide emissions. Several publications highlight that **the application of digital tools can reduce fuel consumption by 10-15%, reduce fertiliser usage by up to 40% and decrease pesticide application by 90%.** This directly translates into lower emissions from both fossil fuel consumption and reduced nitrous oxide emissions due to more precise nitrogen management.

While most of the reviewed publications highlight the positive role of digitalisation in GHG emissions, several also caution that the benefits are not self-evident. The total GHG emissions on a farm may remain steady, or even increase, if productivity gains lead to a greater overall production. This rebound effect means that although the emission per unit of agricultural products (such as litre of milk or kilogram of meat) may decrease, the aggregated impact on climate depends on how the technologies are implemented within the context of a farm. Furthermore, the manufacturing, maintenance and energy use of digital tools themselves can contribute to emissions, though these are often outweighed by the operational savings they enable.

3.2.2 Natural resources

The principle of optimised farm management is essential to achieving more outputs by utilising less agricultural inputs. Based on the thorough review of the collected publications, 14 explicitly examine how precision agriculture and digitalisation enhance the efficiency of farm operations while simultaneously mitigating environmental harm.

The basis of precision agriculture is the principle of data-driven decision-making. Technologies, such as IoTs or remote sensing allow farmers to collect real-time data on soil conditions, input needs, crop- and livestock health conditions. This data enables farmers to apply inputs (e.g. fertilisers, pesticides, water) wherever and whenever necessary, improving resource-use efficiency and minimising waste.

Numerous studies detail how technologies contribute to environmental benefits. For example, the application of variable rate technology (VRT) for fertilisation and irrigation allows inputs to be fine-tuned to the specific needs in different zones within the field. This has been proven to reduce fertiliser

[17] Please refer to Annex II for the list of literature.

[18] Out of the collected publications, 15 explicitly discuss the impact of digitalisation on GHG.

usage by 10-40%, and pesticide use by up to 90%, significantly curbing nutrient runoff, soil degradation, and water pollution.

Moreover, technologies such as controlled traffic farming and automated guidance systems can reduce fuel consumption by 10-15%, while also minimising soil compaction which is a significant factor for land degradation. These operational optimisations not only contribute to a lower carbon footprint, but also extend the productive lifespan of arable land.

Sensors and satellite images enable farmers to track changes in soil moisture, structure, fertility, homogeneity in crops, phenology and weather conditions. These insights facilitate adaptive management that avoids overexploitation and promotes long-term sustainability.

The reviewed literature highlights that precision agriculture does not merely enhance productivity but enables system-wide environmental benefits. These range from improved input efficiency to reduced GHG emission. Importantly, these technologies also support farm profitability, ensuring that environmental goals are not pursued at the expense of economic viability.

Digitalisation of the agricultural sector contributes to the wider European Union strategies

The European Union's Farm to Fork strategy[19] is a central element of the European Green Deal to make food systems fair, healthy and environment friendly. The Farm to Fork strategy aims to ensure sustainable food production by transforming the production methods, and make the best use of nature-based, technological, digital, and space-based solutions which can contribute to better environmental results, increase climate resilience and reduce and optimise the use of agricultural inputs (such as fertilisers and pesticides). **The EU aims to reduce the use of chemical pesticides by 50% by 2030, and fertilisers by 20% by 2030.** The application of digital technologies (e.g. precision agriculture technologies) is proven to reduce the fertiliser needs by 10-40%, and the pesticide use by up to 90%, while the application of remote sensing tools (e.g. sensors) combined with decision support platforms optimise farm inputs. **Blockchain technologies support traceability of agricultural products**, that are especially important in the case of organic products. **Traceability can increase the trust of organic producers**, which can positively affect the demand for such food products. This can indirectly contribute to the EU's goal to increase the agricultural land under organic farming to at least 25% by 2030. The application of precision agriculture technologies can contribute to the **EU's goal to reduce food waste by 10%** in processing and manufacturing by 2030[20]. Remote sensing, decision support platforms and weather forecasting based on real-time data can support the precise harvest timing, significantly cutting food waste in primary production. In post-harvest, sensors and automated storages can optimise the temperature, humidity and gas concentration, essentially extend shelf life and prevent spoilage. Additionally, the application of digital tools in harvesting and post-harvesting can improve the supply chain coordination between producers, processors and retailers.

The EU Soil Strategy for 2030[21] outlines the commitment to sustainable soil management practices, restore degraded soil and mobilise resources to achieve long-term soil health across Europe. As of May 2025, there were 90 soil policy actions, out of which 63 had been completed, while 23 were still in progress and only 4 had been withdrawn[22]. Digitalisation can contribute to the policy actions of the soil strategy through various ways. Remote sensing, in-field sensors and data analysis support the monitoring of soil moisture, organic carbon, pH and nutrient levels to detect degradation early.

[19] European Commission: Farm to Fork strategy. For further information please refer to link.

[20] European Commission: Food waste reduction targets. For further information please refer to link.

[21] European Commission: Soil Strategy for 2030. For further information please refer to link.

[22] European Commission: EU Soil Strategy Actions Tracker. For further information please refer to link.

Decision support platforms support site-specific actions (such as crop rotation, cover cropping, reduced tillage) that improve soil structure and fertility. Harmonised data collection and monitoring efforts across the EU can support the EUSO dashboard[23] with a set of reliable soil indicators integrating trends and foresights, essentially supporting farmers and research likewise. Furthermore, precision agriculture technologies can reduce and prevent soil pollution (e.g. overuse of chemicals).

3.3 Social impacts of digitalisation of agriculture

3.3.1 Social capital

3.3.1.1 Access to digital technologies

Across the relevant publications[24] **a consistent finding emerges that larger farmers are generally better positioned to adapt digital technologies** due to several reinforcing factors. These include access to capital, ability to amortise high fixed costs, availability of skilled labour, and economies of scale. The OECD report highlights that **large farms benefit from lower per-hectare costs** when investing in digital tools and equipment and are more likely to receive bulk input discounts, further boosting their capacity to invest in digital tools.

In contrast, small farms face higher relative costs for adoption. Technologies such as variable rate application, automated monitoring systems, and data integration platforms often require initial investments that are difficult to justify over limited acreage of land. Studies indicate that smallholder farmers are deterred by extended payback periods and low input savings per hectare, making these technologies economically less viable without external support. **Beyond costs, technical, infrastructural and digital literacy skills also hinder the uptake of digital technologies for smallholders**.

The social implication of these disparities is also significant. As noted in the report[25], the digitalisation of the sector often reinforces a productivity-focused model that prioritises efficiency and scale over diversity and tradition. Furthermore, digital technologies are often designed with large farms in mind, and smallholders may be pressured to conform to data-intensive models that do not reflect their economic or agroecological needs.

Several publications highlight the **opportunities for inclusion through tailored approaches**. For example, **shared access models can serve as a key pathway toward equal benefits of digital technologies**. These models include equipment pooling, cooperative ownership of technology and machinery, allowing farmers to access advanced tools without bearing the full cost alone. The role of contractors and third-party service providers is also highlighted as a means to ensure that smallholders can benefit from technological advancements. On the contrary, however, the perception of agricultural collectives varies between the regions of the European Union. Nevertheless, the digitalisation of agriculture has been increasingly shaped by collective structures. **Traditional agricultural collectives have started integrating digital technologies in areas, where access to costly digital tools, fragmented farm sizes, and unequal digital skills present significant challenges.** In some countries, traditional cooperatives have begun integrating digital farm management systems to enable farmers to collectively manage crop cycles, inputs, and sustainability targets. For example, in the Netherlands, cooperatives such as Agrifirm offer members not only joint procurement opportunities, but also digital services including crop modelling, soil testing, and satellite data integration. The Dutch horticulture, particularly greenhouse-based production, has rapidly digitalised with the use of sensors, AI-driven monitoring, and digital twin technologies. These are often implemented through shared service

[23] European Commission: EUSO Soil Degradation Dashboard. For further information please refer to link.

[24] 10 out of the collected publications explicitly cover the inequalities in access, applicability and benefit distribution from digital innovation in agriculture.

[25] Van der Burg et. al. (2019): Ethics of smart farming: Current questions and directions for responsible innovation towards the future.

arrangements supported by cooperatives or public-private innovation programmes. Germany is another great example for cooperations between farmers. The machinery rings (*Maschinenringe*), originally set up for joint use of agricultural equipment, have been operating digital booking systems that allow members to schedule machinery, precision sprayers, or other specialised equipment via applications[26]. This allows farmers to use more advanced technologies without posing significant financial burden on them.

As previously mentioned, the OECD report highlights that **smallholder farmers are less likely to benefit from subsidies aimed at digital innovation**, which are often poorly targeted or require co-financing that many smallholders cannot meet. This calls for **an adjustment in the national and European funding mechanisms** to enable smallholders to equally benefit from these programmes.

Beyond financial models, **education and capacity building are critical enablers of adoption**. The digital knowledge gap disproportionately affects smaller operations, which often lack the personnel or time to engage with trainings. Expanding targeted training programmes, farmer field schools, and digital literacy workshops is essential.

The inclusivity of digital technologies in agriculture also depends on design and governance. Tools and platforms **must be developed with a people-centric approach**, considering the actual needs, workflows and constrains of smallholders. Instead of imposing top-down solutions, inclusive innovation encourages the co-design of technologies with farmers themselves. This can be achieved particularly through participatory projects and collaborative networks that incorporate the voices of smallholder farmers.

Institutional frameworks play a crucial role as well. EU-level initiatives, such as EIP-AGRI, Digital Innovation Hubs or the Smart Village Initiative offer promising blueprints for scaling equitable access. However, the studies highlight that these initiatives must be adequately funded, coordinated between member states, and evaluated for reach and impact among smallholders. The risk of two-speed digital transition in Europe, whereby large and well-resources farms rapidly adopt digital technologies while small or less wealthy farms are left behind, is a major concern addressed across 11 publications. Preventing this divide is critical to achieving an inclusive and sustainable agricultural transformation that benefits all rural communities, rather than deepening existing inequalities.

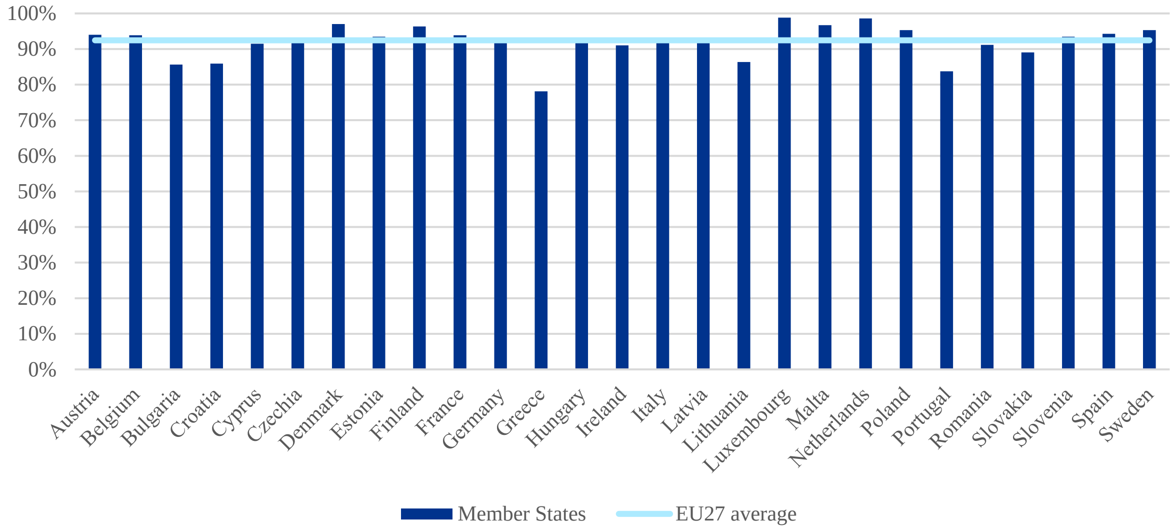
One of the most critical aspects related to the use of digital technologies in agriculture is the need for comprehensive infrastructure investment. Broadband connectivity, IoT networks and digital service platforms must be made universally accessible. In the absence of such infrastructural parity, digital adoption will continue to concentrate in well-connected and more developed regions, exacerbating disparities between farms and member states.

The available information regarding agricultural areas is limited. Usually, agricultural areas are further from settlements, therefore these areas do not benefit from the same prioritisation of providing accessibility as the population. In the absence of this information, the internet access and coverage can be demonstrated through the percentage of rural households that have access to the internet. The highest access was measured in Luxembourg (99.8%), the Netherlands (98.6%), and Denmark (97%), well above the EU27 average of 92.5%, while the lowest were in Bulgaria (85.6%), Portugal (83.8%) and Greece (78.1%)[27] in 2024 (please see the graph below). This entails the significant difference between the EU Member States, which can not only pose limitations towards the uptake of digital technologies in these areas, but also may limit the information regarding the most advanced technologies for farmers and small-scale farmers.

[26] Gscheidle et al (2025): Shared digital agricultural technology on farms in Southern Germany – analysing farm socio-demographic characteristics in an inter-farm context. In Precision Agric 26. Accessed at link.

[27] According to Eurostat: Households – level of internet access. Accessed at link.

Figure 3: Percentage of households located in rural areas with internet access, 2024



Source: KPMG (2025). Based on Eurostat[28].

During the 2014-2020 programming period, the EU member states implemented national and regional rural development programmes (RDPs) with the support of the European Agricultural Fund for Rural Development (EAFRD) under the CAP. According to the ESIF common indicators for the 2014-2020 programming period[29], the EAFRD funds supported a total of 304 512 farm holdings to acquire physical assets and contributed to the training of almost 2.5 million participants overall. Additionally, the RDPs target indicators can shed light on the EU's support towards digitalisation of the agricultural sector. According to the RDPs monitoring data[30], 2.57% of agricultural holdings had been supported for investing in restructuring modernisation, and over 2% of livestock units were concerned by investments in livestock management in view of reducing GHG emission had been supported in the framework of the RDPs. Around 2.2% of the rural population benefited from new or improved ICT services and infrastructures during the same period. Nonetheless, the progress of the indicators had not reached their target values by the end of 2022[31].

However, funding mechanisms must be made more inclusive and flexible to ensure that smallholders have equal access. Many smallholder famers currently struggle to access EU funding steams to support digital transitions, either because of complex administrative requirement or because of eligibility criteria. Publications highlight that aligning the Common Agricultural Policy (CAP), the European Regional Development Fund (ERDF), the Cohesion Funds (CF), the Connecting Europe Facility (CEF), Horizon Europe and other relevant programmes to streamline access and promote public-private partnerships would help to ensure that digital investments can reach the most vulnerable farmers.

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[28]Ibid.

[29]Based on ESIF 2014-2020 Achievement Details timeseries. The latest reported indicators are from 2022. For further information please refer to link.

[30]Latest figures are available from 2022. For further information please refer to link.

[31]According to the CAP transitional regulation (Regulation (EU) 2021/2117), the rural development actions from the 2014-2020 period were extended until the end of 2022. For further information please refer to link.

3.3.1.2 Transformation of workforce

Digitalisation is contributing to a significant transformation of rural labour markets. Digital tools and automation technologies have enabled farms to increase efficiency, often reducing the demand for traditional, low-skilled manual labour. Technologies such as robotic milking systems, automated machinery, and precision crop management systems substitute human labour with capital-intensive equipment. This trend leads to a net reduction of low- and unskilled agricultural jobs, a phenomenon noted particularly in mechanised sectors and in technologically advanced regions of Europe.

There is a growing concern about the potential deskilling or displacement of workers, particularly those with limited education and digital literacy. Furthermore, migrant workers and older generations of farmers may be especially vulnerable to this change. While some roles are being replaced by automated systems, others are being redefined. Digitalisation increases the demand for a hybrid skillset that combine analogue agricultural skills and knowledge with digital proficiencies such as data management, sensor calibration or remote equipment operation. For example, farmers in German dairy sector are now expected to operate digital platforms to monitor and optimise farm operations, requiring a blend of traditional farming knowledge and technical skills.

While traditional roles are being displaced, digitalisation is simultaneously **creating new employment opportunities**. High-skilled jobs in areas such as agricultural data analysis, technology maintenance, remote sensing, and agri-software development are emerging. As noted in several reports, agricultural digitalisation is driving a **bifurcation of the rural labour market**, where highly skilled, technology-savvy workers increasingly benefit from higher wages and better working conditions, while low-skilled workers face job losses or greater exploitation in more surveilled, rationalised workplaces. **This raises concerns regarding labour rights, particularly in terms of job security, surveillance and inequality.** As mentioned previously, digitalisation may lead to labour displacement, especially for low-skilled labour which raises concerns about the erosion of rural employment and the exclusion of workers who lack access to reskilling opportunities. Excessive surveillance and loss of privacy combined with pressure to meet productivity targets poses risks on agricultural workers (including seasonal and migrant workers as well) despite the fact that these systems can enhance accountability and efficiency. In the absence of clear, labour-oriented governance, digitalisation may reinforce exploitative practices under the guise of efficiency.

This bifurcation has significant social and regional implications. Marginalised groups, such as migrant farmworkers and less-educated rural populations, are particularly vulnerable to being excluded from the benefits of the digital transition. Without adequate support structures, such as reskilling programs and accessible digital literacy training, these populations are at risk of deepening inequality and social exclusion.

The literatures also point to positive potential outcomes if digitalisation is managed inclusively. Some rural communities are experiencing an influx of new types of work related to rural digitisation, including services associated with digital connectivity and ICT support. Moreover, digital technologies are seen as potentially making farming more attractive to younger generations by reducing physical drudgery and enabling more flexible, diversified career paths.

Digitalisation holds considerable promise for attracting women and younger generations to farming, although its success in doing so depends greatly on the policy frameworks and support mechanisms in place. Across the assessed literature, digitalisation is consistently presented not merely as a technological innovation, but as a driver of cultural and generational change in the agricultural sector.

Traditionally, farming has been associated with physically demanding labour, financial uncertainty, and a relative lack of technological engagement. These factors have historically **discouraged younger individuals and women from entering the field**, especially in regions where agriculture is seen as outdated or unappealing. Digitalisation challenges this narrative by reimagining farming as a profession rooted in data, innovation, environmental stewardship and essentially increasing working conditions. Technologies such as precision agriculture, drones, artificial intelligence, and remote sensing allow farms to operate more efficiently and sustainably. These tools shift the role of the farmer from one of manual labour to that of a systems manager, someone who analyses data, interprets trends, and makes strategic decisions. **This shift in the role of individuals in farming can increase the involvement of women and younger generations** in the traditionally male dominated sector. For many people, particularly those with technical skills or environmental concerns, this transformation makes agriculture more intellectually engaging and aligned with broader societal values like sustainability and innovation.

The growing practice of advertising agricultural jobs online (such as through local job portals or social media platforms) **has reshaped the recruitment landscape for seasonal and migrant labour across the European Union.** Traditionally reliant on informal networks or local intermediaries, agricultural employers now increasingly use digital platforms to advertise vacancies, often targeting workers in lower-income EU countries or neighbouring non-EU countries. While this shift introduces a degree of transparency and reach into recruitment processes, it also carries complex implications, particularly for the structure and stability of labour migration patterns and the socio-economic impacts on workers' countries of origin. **Online advertisement of agricultural jobs has contributed to the acceleration of intra-EU labour mobility**, often drawing large number of workers from economically weaker regions, mostly from Eastern Europe and Western Balkans. **This can lead to a labour shortage in the agricultural sectors in these countries**, potentially weakening local food production systems. Furthermore, online advertisements may disguise poor working conditions, unclear contracts or legal ambiguities regarding social protections. On the other hand, however, remittances contribute to increased household incomes and local development. Younger and more digitally literate workers are more likely to seek employment abroad, deepening the generational gaps in the rural workforce. Over time, this may lead to structural dependencies on external labour markets.

However, **the ability of digitalisation to draw new generations into agriculture does not arise automatically**. Without supportive policies, the benefits of digital tools may remain inaccessible or unappealing to young entrants, particularly in rural or economically disadvantaged regions. The literature emphasises that structural barriers (such as limited access to land, capital, and tailored training) remain significant hurdles. Digitalisation must therefore be embedded within a broader enabling environment that includes public investment, education reform, and inclusive innovation systems.

In a way, young farmers face similar barriers and challenges to smallholder farmers. Young people often lack the collateral and/or capital to invest in advanced technologies. Funds and subsidised access to digital tools, and targeted grants can mitigate this challenge. The integration of these financial supports with mentoring programs and peer learning networks helps not only to build technical capacity but also to foster a sense of community and purpose. According to the literature, such networks can reduce the isolation often experienced by new entrants and reinforce digital competence as a shared norm among younger farmers.

If digital agriculture becomes synonymous with large-scale, capital-intensive operations, it risks reinforcing generational and socio-economic divides. Policies must therefore ensure that digitalisation is not only about scaling technology but also about creating inclusive systems that value diverse farm sizes, business models, and cultural contexts. Public-private partnerships, open-source platforms, and collaborative innovation ecosystems are highlighted in the document as essential vehicles for democratising access to technology.

3.3.2 Individuals

According to the literature, the adoption of digital technologies among farmers is influenced by a complex interplay of individual, organisation, technological and contextual factors. These drivers and barriers vary significantly by farm type, scale, and the personal characteristics of the farmers.

Individual-level factors such as education, experience, and digital skills are among the most consistently cited drivers. Farmers with higher levels of education and digital literacy are more likely to adopt precision tools, data platforms, and sensor-based technologies. This is partly due to the fact that these tools require a certain level of confidence and familiarity with data interpretation and system operation. In contrast, older farmers may be less inclined to adopt due to lower digital literacy and reluctance to invest time in learning new systems – although age alone is not a consistent predictor, as attitudes and complexity of the technologies also play key roles.

As previously discussed, **farm size is another dominant factor** due to economic of scale. Large farms are more likely to spread the high fixed costs of digital equipment over large areas, making the investment more economically viable. Large farms also often have better access to capital, external services, and specialised staff, all of which facilitate adoption. Conversely, small and medium-sized farms often face significant cost barriers and lack access to advisory support or tailored services, which can hinder the uptake of digital technologies.

Technology- and infrastructure-related challenges also play a central role in shaping adoption. Farmers are less likely to adopt technologies if the technology is perceived as too complex, incompatible with their existing equipment, requiring significant learning or behavioural change or not personalised for their needs. If the benefits of adoption (e.g. yield gains, cost savings, environmental advantages) are unclear or hard to measure, farmers perceive the risks as outweighing the potential rewards. Concerns regarding data ownership, privacy and how data is shared with third-party providers further discourage the adoption of digital technologies.

Contextual factors, such as market conditions, policy incentives, and peer networks also affect adoption. For example, access to digital innovation hubs, extension services, or farmer cooperatives can significantly increase the likelihood of adoption by reducing knowledge gaps and creating supportive communities of practice. Policy instruments (such as subsidies for digital tools, grants for trainings or advisory services) can play a catalytic role, especially for early adopters in disadvantaged regions.

3.4 Economic impacts of digitalisation of agriculture

3.4.1 Organisation

3.4.1.1 Investment costs associated with adopting digital farming technologies

Farms face a broad range of investment costs when adopting digital technologies. The cost depends on the type of technology, often including both hardware (such as sensors, drones, robotic milking or feeding equipment) and software (such as decision support tools or farm management systems). Collecting information on investment costs related to digital technologies are challenging due to the heterogeneity of technologies, farm-specific conditions and requirements, lack of transparent market data as most technologies are sold through private arrangements, evolving business models (e.g. Services-as-a-Service model), among others. Despite these challenges, we aimed to collect available information and estimates on investment costs of the most typical technologies in agriculture. The typical cost ranges of key digital farming technologies are summarised in the table below.

Table 4: Likeliness of adopting digital technologies by attributes

Attributes	Likeliness to adopt digital technologies			
	Low	Moderate	High	Very High
Geography	Eastern EU	Southern EU		Northern / Western EU
Farm size	Small farms		Medium farms	Large farms
Agricultural sector	Extensive livestock (e.g. sheep, beef)	Poultry	Arable sector Dairy sector	Horticulture
Age of farmers	Older farmers			Younger farmers
Level of training and education	No formal education		Formal education	
Succession	No formal successor		Formal successor	
Financial status	Financially constrained farms		High-income farms	

Source: KPMG (2025).

Table 5: Typical costs of key digital farming technologies, estimation based on the collected literature (2020-2025)

Type of technology	Typical cost range (EUR)	Notes
Field sensors and IoT devices	400 – 2 000 EUR per unit	This includes basic weather stations, soil moisture sensors, climate sensors. The price varies depending on the complexity of the solution.
Farm management software	Up to 20 EUR / hectare	Farm management software or decision support tools are typically low-cost or free, while advanced services using sensors / satellite data may cost more.
Precision sprayers	3 000 EUR to 40 000 EUR	The cost of variable-rate sprayers highly depends on their complexity. More simple solutions (e.g. the ones requiring manual mapping) are usually on the lower-end of the range, while camera-based dose modulation is on the higher-end range.
Machine Guidance and Auto-Steering	1 300 EUR to 50 000 EUR	A simpler, GPS guidance for tractors starts from 1 300 EUR, while auto-steering and Controlled Traffic Farming solutions are more expensive.
Robotics for horticulture and crop production	25 000 EUR to 80 000 EUR	Robotics are more advanced, therefore more expensive solutions in digital agriculture. This includes e.g. weeding robots, starting from 25 000 EUR on average.
Precision Irrigation Systems	1 300 EUR to 35 000 EUR	Pivot irrigation controllers start at around 1 300 EUR, while advanced pivot management systems can cost up to 35 000 EUR. However, drip irrigation infrastructure costs around 40 EUR per hectare.
Livestock Wearable Sensors	120 EUR per sensors, and infrastructure costs	Sensors, e.g. cow monitoring collars costs around 120 EUR each, plus around 4 000 EUR for the infrastructure. Software fees can increase the cost of investment by around 180 EUR annually.
Robotic Milking System	1 500 EUR / animal	The estimated price for robotic milking systems is around 1 500 EUR / animal[32].
Automated Feeding System	1500 EUR / animal	The estimated price for an automated feeding mixer is around 230 000 EUR for a farm with around 150 cows.
Training and IT Support	400 EUR – 1 400 EUR	Training farmers to use new digital tools is essential. Courses and consulting typically cost a few hundred EUR.

Source: KPMG (2025). Based on the reviewed literature listed in Annex II[33].

3.4.1.2 Cost-benefits of digital technology adoption on farms

The economic benefits of the application of digital technologies on a farm level stems from **productivity gains (in terms of volume, labour and efficiency) and input savings.** Based on the literature review, **the application of digital tools in crop production can increase yields by 10-15%** and **reduce fertiliser and pesticide use by 10-30%.** These improvements are primarily driven by precision farming technologies (such as variable rate technologies, remote sensing, and data driven decision support). **The use of digital tools in livestock production, more precisely in milk production, can increase outputs by 10-15% and reduce food waste by 5-10% and energy use by 35%.** These gains are linked to the adoption of precision livestock farming technologies, including automated milking systems, sensor-based health monitoring and smart feeding technologies. **The use of digital tools in horticulture** increases yields as well, but the benefits **are rather demonstrated in water savings (by 20-30%) and reduced fertilisers (between 18-33%).** These outcomes are largely enabled by smart irrigation systems,

[32] According to the literature review, a Robotic Milking System costs around 120 000 EUR for an average farm with 80 cows.

[33] The cost range of technologies were identified based on the collected literature. Please note that the prices shown were calculated from the materials collected at the time of analysis and may not reflect current market prices. The costs shall be critically evaluated in light of underlying assumptions, methodologies, and context for each source.

such as drip irrigation integrated with soil moistures sensors and climate forecasting tools allowing farmers to apply precise water quantity. Similarly, on average the digitalisation of irrigation systems leads to 20-40% water savings, yet higher savings can be achieved as well.

These factors can lead to increased profitability, and hence, return on investment rates on farm level as well. Returns on investment are generally positive, especially when technologies are scaled or integrated effectively. It is highlighted that smaller farms face relatively higher upfront costs and scalability challenges due to their farm structures as detailed previously. In additional to quantifiable gains in yields, cost savings, and labour productivity, the application of digital technologies in agriculture delivers qualitative benefits as well such as enhanced environmental sustainability (reduced water, fertiliser and pesticide use), improved animal welfare, and greater resilience against climate change induced effects and diseases.

Table 6: Cost-benefits metrics of digital technologies in different sectors, based on the collected literature

Sector	Crop production	Livestock	Horticulture	Irrigation
Productivity gains	Yield increases by 10-15%	Milk production 10-15% Better weight gains and product quality in meat	Higher yields, Increased quality and consistency	n/a
Input cost savings	Reduced fertiliser and pesticide by 10-30% Targeted spraying up to 90% 10% of fuel saving	Feed waste reduced by 5-10% Energy use reduced by 35% with robotics	Water saving by 20-30% Reduced fertiliser use (between 18-33%)	Commonly 20-40% less water usage, up to 50-75% water savings
Labour and efficiency	Higher labour productivity	Major labour reduction by automation (milking)	Labour-intensive tasks partly automated (up to 20%)	Automation reduces manual irrigation labour
ROI and profitability	Positive in most cases, approx. +5%	High, long-term ROI due to decreased labour saving and more and better output	Generally positive and strong ROI, in some cases up to 78%	High cost-effectiveness, typically full ROI in 1-3 years from water and energy savings

Source: KPMG (2025). Based on the reviewed materials listed in Annex II[34].

3.4.1.3 Factors hindering or driving the adoption of digital technologies

The uptake of digital technologies varies strongly by regions and farm sizes. Twelve out of the collected publications explicitly explores the challenges European farmers face in adopting digital tools and technologies in agriculture. According to a recent survey[35] larger farmers are more likely to adopt advanced precision agriculture technologies, whereas smaller farms tend to utilise more simple solutions (e.g. farm management software, simpler weather stations, or analogue sensors). At the same time, the same survey highlighted that only 46% of European farmers have adopted at least one technology in agriculture compared to 74% of farmers in the US, and 53% in Brazil[36].

One of the most pervasive barriers citied across Europe is the high cost of digital tools, especially for small and medium-sized farms. Technologies, such as variable rate fertilisation, automated guidance systems, and livestock monitoring sensors require significant upfront investment. Although larger,

[34] Note that the figures are extracted from the synthesis of the collected literature listed in Annex II and are provided for informational purposes only. and shall be critically evaluated in light of the underlying assumptions, methodologies, and context of each source.

[35] McKinsey (2024): Global Farmer Insights 2024. Accessed at link.

[36] The average farm sizes vary in the US, Brazil and Europe. The average farm size in Europe is 180 hectares compared to 1 300 in Brazil and 14 500 hectares in the US. This contributes to the disparity as well between Europe, the US, and Brazil.

capital-intensive farms in North-West Europe (e.g. Germany, Denmark, the Netherlands) have increasingly integrated such tools, small farms – that make up the majority of farms in southern and eastern Europe – often lack the capital to invest. The high investment costs of digital farming technologies are often cited as one of the major barriers to adoption. Beyond the equipment costs, farmers must account for integration and downtime costs (installing and calibrating new systems), learning curve and training expenses, continuous costs for maintenance, repairs and updates. **Small farms in particular struggle with the ROI of precision technologies**. In the absence of economies of scale, it can take many years of input savings / productivity gains to earn back the initial investment. The OECD report[37] highlights that smaller farms are not only less likely to adopt precision technologies but are also less likely to benefit from subsidies aimed at digital innovation, which are often poorly targeted or require co-financing that many smallholders cannot meet.

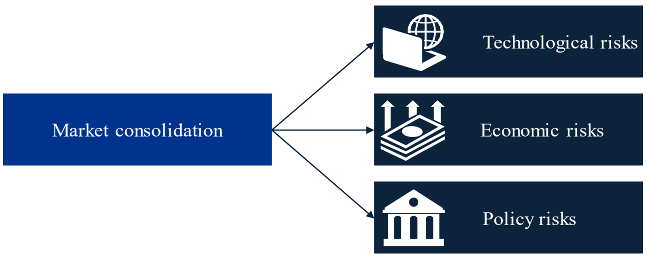
Technical complexity is another significant hurdle. The design of many digital tools does not reflect on the needs of small-scale and diversified European farms. Farmers often perceive the technologies as too complex or misaligned with their specific needs. The issue is compounded by limited access to user-friendly training and advisory services. This is particularly true in parts of southern and eastern Europe, where an older farmer population dominates[38], and digital literacy rates remain low[39]. Studies highlight the knowledge gap as a key barrier preventing farmers from effectively implementing digital systems that could reduce fertiliser use, optimise resource efficiency, and ultimately lower GHG emissions.

Regional differences within Europe also influence adoption patterns. In western and northern Europe, the relatively strong infrastructure, public support schemes, and better digital ecosystems have facilitated broader uptake. However, in southern and eastern regions poorer rural internet coverage, underdeveloped agri-tech support networks, and bureaucratic barriers in accessing EU innovation funds hinders the adaptation of digital technologies in agriculture. Even when the technologies are available, these systemic limitations mean that their adoption for GHG reduction purposes remains limited and fragmented.

Social and institutional factors further hinder adoption. The literature review highlights that trust in technology providers and public institutions affects the willingness of farmers to share data or engage in precision farming platforms. Concerns around data privacy, unclear ownership of information, and fear of surveillance have led many farmers to reject potentially beneficial systems. Moreover, gender and generational inequalities exacerbate digital expulsion, as younger, more digitally literate farmers tend to have better access to training and capital, while older farmers are less likely to be targeted by tech outreach initiatives.

3.4.2 Markets

Figure 4: Risks of market consolidation



Source: KPMG (2025).

Corporate consolidation in the agri-tech sector provides mixed advantages. On the one hand, well capitalised farms can deploy digital innovations at scale, benefitting from integrated solutions. On the other hand, however, as the literature review showed, consolidation carries **significant technological, economic and policy risks** that could undermine the very goal of digital agriculture to increase productivity via data-driven solutions.

[37] OECD (2022): The digitalisation of agriculture. A literature review and emerging policy issues.

[38] According to Eurostat, over 57% of farmers are 55 years old or older on EU27 level. For further information please refer to link.

[39] According to Eurostat, over 55% of the individuals aged 16-74 have basic or above digital skills on EU27 level. For further information please refer to link.

3.4.2.1 Technological risks of market consolidation in agri-tech

Technological risks are associated with data control, interoperability and innovation of the agri-tech sector. As a handful of dominant firms can gain influence over both hardware and digital services, farmers may find themselves increasingly locked into closed ecosystems where switching providers is costly or impossible. **Interoperability challenges and data silos limit flexibility and autonomy**. The data consolidation can cause technological lock-ins with closed ecosystems due to non-interoperable data. This threatens the farmers' ability to switch platforms in fear of losing valuable data history or insights. The EU Data Act explicitly tackles device data lock-ins as it aims to empower EU users of connected devices to access the data generated by these products and share it with third parties, e.g. an independent farm advisor service provider.

Additionally, the centralisation of farm data under corporate platforms can compromise farmers' control over their own operational intelligence. The corporations controlling these data have strong incentives to monetise the information (e.g. selling analytic services or related products) and little incentive to openly share this information to farmers or public researchers. Furthermore, even if farmers own their raw data from their farm, the company owns the aggregated, pooled and analysed data from all farms utilising the given solution. This creates significant imbalance between individual farms and large companies. Since the platform operators own the aggregated data, the farmers cannot erase their contributed data in case they leave the platform or service provider. If a farmer's data has been integrated into a collective analysis, it cannot be removed.

A dynamic and competitive environment is usually a catalyst for innovation, however, in consolidated agri-tech environment the innovation can be stifled. Smaller, start-up firms may find it more difficult to offer competing products for farmers in the absence of access to data at scale. This entails that already well-established enterprises have inherent advantage by having their data volume. This can lead to network effects, as farmers gravitate to platforms that already have the most data and users, increasing market consolidation further.

Digital sovereignty and autonomy driven by data

Digital sovereignty in agriculture refers to the ability of farmers, and the EU as a whole, to control the digital tools, data and infrastructure that underpin modern farming.

From the farmers' perspective, digital sovereignty means having the right and practical ability to access, own and manage their farm data, choose among interoperable tools, and avoid dependency on a single vendor for essential decision-making processes. Without these rights, farmers risk becoming passive users in closed corporate ecosystems, where their knowledge, practices, and data are commodified without fair return.

From the EU's perspective, digital sovereignty involves ensuring that Europe's agricultural sector in not reliant on non-EU owned platforms or data infrastructures, which could pose economic, strategic or even food security risks. The concentration of digital power in the hands of a few multinational companies may undermine the EU's goals for a competitive, sustainable and farmer-driven food system.

3.4.2.2 Economic risks of market consolidation in agri-tech

Market consolidation in the agri-tech sector presents growing economic risks for EU farmers, particularly concerning affordability, equitable access, and long-term competitiveness. As a handful of major corporations acquire digital service providers and integrate software with their input and machinery portfolios, pricing power becomes increasingly concentrated. This allows dominant providers to impose higher costs for digital tools (such as farm management software, precision equipment add-ons, or analytics platforms) with little pressure from competitors to maintain affordability. In practice, this often translates into subscription-based models, bundled services, or exclusive loyalty schemes that are more accessible to large commercial farms, but out of reach for many smaller or resource-constrained holdings.

The result is a deepening of the digital divide between large and small farms. While large farms can more easily absorb the costs of digitalisation and benefit from the economies of scale, smaller farms, representing the majority of EU holdings, are often unable to justify the upfront investment or recurring costs, even if long-term benefits exist as detailed earlier. This economic exclusion threatens to reinforce structural inequalities within EU agriculture, undermining cohesion and rural resilience. Moreover, vendor lock-in practices (such as requiring farmers to buy inputs from the same company that provides their digital services) further reduce flexibility, and expose farms to price volatility and contractual dependencies. Farmers who are unable to switch platforms without losing access to their own data or accumulated insights may find themselves trapped in systems that erode their margins and autonomy over time. Without intervention, these economic asymmetries risk accelerating the decline of small farms and concentrating technological and economic power in the hands of a few agri-tech enterprises.

In the European agri-food supply chain, the burden of unfair trading practices (UTPs) disproportionately falls on farmers, who are structurally considered the weakest actors in the value chain. Retailers and large agri-food companies may require their suppliers to adopt digital technologies to provide real-time data, trade product origins, and ensure compliance with environmental standards. While such measures ostensibly promote transparency and consumer trust, they often come without adequate support or cost-sharing mechanisms for the farmers. **The European Commission adopted the Directive (EU) 2019/633[40] on unfair trading practices (UTP)** in the food supply chain in 2019. The Directive bans 16 unfair practices (such as late payments for perishable and non-perishable agri-food products, short-notice cancellations of perishable agri-food products or payment for unrelated services[41]), **however, increased demand for transparency measures can still pose risks on farmers**. Retailers may demand full traceability of produce from "farm to fork" using digital systems such as QR-coded labels, blockchain-based platforms, or precision data logs. While these technologies can be beneficial in the long run, their upfront investment costs, maintenance, training requirements, and data reporting obligations can pose significant burden on farmers, especially small-scale farms. Moreover, such demands can be often made unilaterally or with limited negotiation, creating a dynamic where farmers must either comply or risk losing market access. This asymmetry shifts compliance costs downstream and reinforces structural inequalities where farmers are expected to deliver more information, take on digital responsibilities, and upgrade their operations whereas they may not financially benefit from the final product price. Additionally, the data generated through these systems may not be controlled or owned by the farmers, but by the platforms or retailers. This can raise concern about data sovereignty an reinforce dependence.

3.4.2.3 Policy risks of market consolidation in agri-tech

The consolidation of agri-tech markets has progressed more rapidly than the evolution of the EU's regulatory and policy frameworks, giving rise to a series of institutional and governance risks. Traditional competition policy tools are not fully adapted to the digital platform economy, especially if market dominance stems from control over agricultural data, algorithmic recommendations, or integrated service ecosystems rather than classic price-setting or output manipulation. Mergers, acquisitions or sole partnerships in the agri-tech sphere, which happen often between agrochemical players and machinery companies, have proceeded without rigorous scrutiny of their long-term implications for farmer autonomy, market access, and innovation. The data-driven nature of these markets means that first-mover advantages can quickly become entrenched, with new companies facing high barriers to entry due to lack of access to comparable datasets or customer bases.

Moreover, EU policy instruments can risk reinforcing consolidation unintentionally. For example, if CAP eco-schemes or sustainability-linked subsidy frameworks require specific forms of digital

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[40] Directive (EU) 2019/633 of the European Parliament and of the Council of 17 April 2019 on unfair trading practices in business-to-business relationships in the agricultural and food supply chain. Accessed at link.

[41] For further information please refer to link.

reporting or traceability, and only a few dominant platforms offer such functionality, public funds may de facto endorse and expand private monopolies. Similarly, digital compliance tools tied to climate-smart farming or carbon accounting may consolidate control over how sustainability is measured and monetised. While initiatives like the EU Data Act and the Common European Agricultural Data Space (CEADS) are steps in the right direction, seeking to enhance data portability, interoperability, and user access rights, they are still in early stages of implementation. Their ability to counterbalance existing power asymmetries will depend heavily on enforcement, technical standards, and the promotion of open-source and farmer-centric alternatives.

Without stronger safeguards, the EU faces the risk of a digital transition shaped not by public policy or farmer needs, but by a small number of vertically integrated corporations. This would counter the EU's goals of fostering fair competition, inclusive innovation, and a sustainable food system grounded in diversity and resilience. This calls for a proactive policy response that includes updated antitrust rules for data-driven markets, procurement conditions that prioritise open systems, and dedicated support for digital tools designed by or for smallholders.

3.4.2.4 Agricultural data governance and safeguards for fair competitions and data rights

According to the literature review, **the governance of agricultural data remains uneven and fragmented across the EU**, essentially raising complex challenges around ownership, access, use and control.

At the EU level, efforts are underway to establish a coherent governance framework that ensures fairness and transparency of agricultural data. **Regulatory instruments, such as the General Data Protection Regulation (GDPR), the Data Act[42], the European Data Governance Act[43] lay the basis for protecting personal data and enabling trusted data sharing.** Additionally, sector-specific initiatives such as the Code of Conduct on Agricultural Data Sharing by Contractual Agreement[44], and EU-backed platforms such as AgriDataSpace (CEADS) and Digital Europe aim to promote farmer-centric data ecosystems and interoperable digital infrastructures.

Despite these efforts, several structural vulnerabilities remain. Agricultural data is often governed by private contracts between farmers and technology providers. Due to the contractual nature of data sharing, the generated data on farms is controlled by agri-tech companies that manage the platforms, devices and analytics systems, creating an imbalance where farmers generate the data, yet lack effective ownership over its use.

To ensure the fair competitiveness and fair use of data, it is important to strengthen the data portability, and open governance structures. Promising solutions include cooperative models for data sharing, public investments in neutral digital infrastructure, and mandatory transparency in data contracts. The EU's push for a common European data space, including one dedicated to agriculture, is a step toward a more democratic and inclusive data governance in the sector.

[42] For further information please refer to the European Commission: Data Act. Accessed at link.

[43] For further information please refer to the European Commission: European Data Governance Act. Accessed at link.

[44] For further information please refer to the link.

4. Presentation of the case studies

Figure 5: The selected Member States covered by case studies

Source: KPMG (2025).

The case studies aimed to cover the regional diversity of the European Union, among other aspects such as the level of digitalisation and diversity of main agricultural outputs. In this respect, the case study-based analyses cover **Estonia, Germany, Romania** and **Spain**. Furthermore, thematic focus of each case studies was outlined to demonstrate an aspect where the selected country excels in digitalisation in the agricultural sector. The **Estonian** case focuses on the **enabling environment** that supports the uptake of digital technologies in the agricultural sector. The **German** case study focuses on **organic production**, which has not only positive environmental effects, but can provide a higher income for farmers. The **Romanian** case study focuses on the use of digital technologies in crop production as well as outlining the uptake of digital technologies from **a social aspect**, where the land remains fragmented, and the farmers face financial barriers to invest in digital technologies. The **Spanish** case focuses on the **use of digital technologies in irrigation** to demonstrate how digitalisation can support sustainability and resources efficiency in agriculture. The case studies were developed utilising targeted desk research and complemented by seven stakeholder interviews. The interviewed stakeholders from each Member State can be found in Annex III.

4.1 Case study from Estonia

4.1.1 Context

Over the past decade, Estonia's agricultural sector has witnessed a steady growth in output. In 2013, the gross value added (GVA) of the primary sector (agriculture, forestry and fishing) stood at EUR 584 million. By 2023, this had increased to EUR 763 million, reflecting a compound annual growth rate of approx. 3.2%[45]. Comprehensively, the sector represented about 2.2% of Estonia's total GVA, slightly above the EU average of 1.8%.

In terms of employment, the agricultural sector provided jobs for an average of 21 135 people in 2024, accounting for roughly 3% of the national workforce. This share is slightly below the EU average of 4%. Employment in the sector is highly seasonal, with workforce numbers fluctuating by nearly 5 000 between the first and fourth quarters of the year[46].

Land use patterns in Estonia have remained relatively stable over the last decade. Between 2010 and 2023, the total Utilised Agricultural Area (UAA) showed little overall change and stood at 0.9 million hectares in 2023[47]. Out of the country's agricultural land, 71% is arable, 27% is permanent grassland and meadows, while only 0.4% is allocated to permanent crops. Between 2010 and 2020, the number of farms declined sharply from 19 610 to 11 370, leading to a substantial increase in average farm size from 48 to 86 hectares. This indicates a moderate consolidation in the sector, while productivity has generally kept pace or grown modestly[48], while in some segments the productivity increased

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[45]Eurostat: Gross value added and income by detailed industry (NACE Rev.2)

[46]Eurostat: Employment by NACE Rev.2 - thousand persons. Accessed at link.

[47]Eurostat: Utilised agricultural area by categories. Accessed at link.

[48]The output of the agricultural industry increased from EUR 900 million in 2014 to almost EUR 1.3 billion in 2024. According to Eurostat, accessed at link.

significantly such as milk production[49]. Livestock production has remained relatively stable during the same period, with around 300 000 livestock units and a density of 0.3 LSU per hectare[50], while the output of livestock has increased during the same period from EUR 451 million in 2013 to 636 million in 2024[51].

In economic terms, the sector has faced challenges in recent years. Entrepreneurial income was negative in both 2023 and 2024 (EUR -55 million and EUR -64 million respectively), raising concerns about the long-term economic viability of the sector. Revenues in 2024 were primarily driven by animal output (EUR 385 million) and crop output (EUR 317 million), though together those represented just around 0.1% of total output of the EU Member States collectively. Within this structure, milk was the leading product, accounting for 33% of Estonia's total agricultural output, followed by cereals (including seeds) at 20.4%.

Estonia relies on importing agricultural goods, maintaining a negative trade balance in agricultural goods. Between 2012 and 2022, the country recorded an average annual deficit of EUR 326 million in agri-food trade. In 2022, Estonia exported EUR 1.7 billion worth of agricultural products, mainly consisting of basic commodities (accounting for EUR 622 million), while imports reached almost EUR 2 billion in the same year. The main import categories included food preparations (EUR 482 million) and other primary products (EUR 478 million) [35]. Regardless of nation's limited agricultural footprint on an EU level, Estonia is considered as one of the most advanced countries in terms of e-government services, exhibiting various novel digital solutions in the agricultural sector as well.

4.1.2 Specific context

Estonia is one of the most advanced countries in Europe when it comes to digitalisation[52]. At the core of the Estonian e-government ecosystem is the X-Road, a secure data exchange layer that enables interoperability between diverse information systems. This system allows seamless data sharing across governmental agencies, private enterprises, and individuals, ensuring confidentiality and integrity. The national e-ID system complements this ecosystem, providing citizens with secure digital identity to access a wide range of e-services.

X-Road is a centrally managed distributed Data Exchange Layer that enables different information systems to communicate securely over the internet. Rather than centralising all data in one place, the X-Road infrastructure enables each organisation to retain control over its own data while making it accessible to others under strict conditions. In other words, this system is decentralised for resilience and autonomy, but centrally governed for trust and consistency. X-Road does not create or store any data, thus avoids a single point of failure and enhances privacy. It acts as a middleware layer, standardising how data is requested, transmitted, and received between different systems. Each organisation connects its system via a secure adapter called a Security Server. It ensures that only verified members can participate in the system. Furthermore, it encrypts all data exchanged and logs every transaction for auditing and transparency. One of the key features is standardisation; APIs and data formats are standardised for compatibility.

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[49] The milk production increased from 3 500 kgs / cow in 1992 to 10 600 kgs/cow in 2023 on average. For further information please refer to link.

[50] European Commission: Analytical Factsheet - Estonia

[51] Eurostat: Economic account for agriculture- values at current prices. Accessed at link.

[52] According to the Digital Economy and Society Index (DESI) 2022, Estonia ranked first on digital public services and ranked 9th of the combined Digital Economy and Society Index in the EU27. For further information please refer to link.

Agriculture is no exception to the digital transformation in Estonia. Built on the X-Road system, data sharing and communication between government institutions, private sector actors, farmers and research entities benefit the agricultural sector as well in the country.

4.1.3 Digital Transformation in Agriculture

The digital transformation of the agricultural sector began with the recognition of data becoming a significant aspect of agricultural production. To effectively manage farms, access subsidies, monitor livestock, and meet environmental regulations, farmers needed to interact with numerous institutions. Traditionally, this involved time- and resource-consuming paperwork, and fragmented systems. Estonia managed to overcome this challenge not by building a single centralised agricultural database, but by integrating existing systems through X-Road.

One of the most impactful applications of X-Road in agriculture, is the **Agricultural Registers and Information Board (ARIB**) that serves as the central platform for managing agricultural subsidies, grants, and rural development programmes. X-Road links ARIB with land registries, the tax board, and environmental monitoring systems which allows for real-time verification of land ownership, tax compliance, and eligibility conditions without requiring the farmer to submit the same information multiple times. ARIB's digital services allow farmers to conveniently apply for EU subsidies, update land parcel details, and track of the progress of their application processes. However, changes in grant and payment regulations can pose challenges, particularly for small businesses, which may struggle to follow the changing requirements. Additionally, delays in processing grant applications can negatively impact farmers. For example, by hindering the perchance of necessary equipment, delaying essential maintenance, or causing them to miss opportunities to expand into new markets or improve their productivity. The use of ARIB results in faster, more transparent, and less error-prone process that builds trust among all parties.

Both livestock management and crop production benefit from this infrastructure. Animal movement records, veterinary data, and identification systems for livestock production are all connected via X-Road, enabling both national and EU-level traceability. When an animal is sold, vaccinated, or exported, the necessary updates ripple across all relevant systems almost instantaneously. **In practice, there are several tools that are integrated with X-Road to manage livestock**. **The Estonian Livestock Performance Recording system is one of them**, which is used by cattle farmers to track breeding data, milk yields, and health events. This system connects with national veterinary databases, so vaccination records and disease reports are updated automatically. **The Veterinary and Food Board Information System is another core platform**, along real-time tracking of animal health and movement, which supports food safety and disease outbreak response. These tools not only increase efficiency but are vital in meeting regulations on traceability and animal welfare. The implementation of digital tools to monitor herd health, and the statistics available from the collected data in livestock production contributed to Estonia reaching the highest productivity of raw milk production in the EU. While the average raw milk production stood at 7 791 kg per dairy cow in 2023 in the EU, the Estonian annual yields reached 10 728 kg per dairy cow in the same year[53]. According to the stakeholder interviews, digitalisation and precise digital tools that were shaped for the Estonian context helped to reach the highest raw milk productivity in the European Union. This underlines the fact that personalised solutions serve as the backbone of increased productivity in agricultural production.

Beyond governmental portals, several innovation projects aim at livestock production in Estonia. While having significant volumes of information available on a national level, the practical use of the databases remains relatively low, especially in a cross-industry setting. **One of the key projects is the beefEST, which aims to connect various datasets in one single management application[54]**. This

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[53] According to Eurostat. For further information please refer to link.

[54] For further information on beefESt, please refer to this link.

combines livestock data (e.g. breeding data, data concerning parentage with daily animal health data, herd and pasture management information) with data from various agricultural fields, their vegetations and declarations of activities. Usually, these datasets are managed separately in silos, while combining this information can create an improved herd management system through the utilisation of data. In general, the innovation projects aim to improve the use of collected data.

Crop monitoring, often driven by satellite imagery, drones or field sensors, is integrated with government and private-sector systems in a similar way. When damage assessment is needed due to drought, flooding or disease, the national X-Road system enables insurers, advisory services, and public agencies to access consistent and verified data. This enables quicker decisions, as well as more accurate impact assessments. Farmers rely on platforms such as eAgronom or Tereka. These platforms enable farmers to track crop cycles, input use and field operations. These platforms are connected with the ARIB to align records on field declarations, land use, and subsidy eligibility. By utilising data from weather stations, soil sensors, and remote sensing, the platforms offer real-time insights into crop performance and forecasts disease or nutrient deficiencies. Another platform is FoodDocs, an award winning Estonian digital application for food safety management. The platform, developed for food producers and processors (including farm fairies or on-farm food businesses), digitalises the mandatory food safety plans and checklists. It was developed in collaboration with the Ministry of Rural Affairs and the Food Authority for their specific business needs, and it saves time and helps even small agricultural processors to maintain proper safety documentation[55]. These examples illustrate how the broader digital transformation supports agriculture from multiple angles, from administrative streamlining by government to private-sector tools that leverage open data and e-regulations to add value on a farm level.

The measurable benefits of Estonia's digital agriculture push are evident in efficiency gains and improved services. **Administrative burdens for farmers have been sharply reduced**, while tasks such as subsidy application, compliance reporting, and record updates can be completed faster and with fewer errors. This essentially frees farmers' time for other activities. Automation and data exchange have also improved the quality and speed of government oversights, as many control procedures can be done via digital checks or remote sensing, making mandatory audits more precise and less intrusive. This has translated into timely payments, and fewer disputes in subsidy control. Additionally, having a rich database available (e.g. detailed soil maps and herd performance metrics) enables more informed decision-making on the farm. Farmers can optimise inputs and practices using digital decision-support tools, potentially improving yields and reducing costs. There are also spillover benefits. For example, digital transparency builds trust among parties as both farmers and the public can see where support funds go, how the rules are followed, and the modern image of e-agriculture helps attracting younger generations to farming. Notably, the digital system proved to be resilient during the COVID-19 pandemic, eliminating the need for physical visits due to the online platforms.

Despite the advanced state of digitalisation in Estonia, the country also experiences challenges when it comes to digitalisation. The gap in digital skills and inclusion remains a hindering factor in the country as well. The interviews and the reviewed materials highlight the need to provide support, training and advisory services to ensure that everyone can use and benefit from the e-services effectively. Even when digital tools are available, using data for decisions can be difficult. Farmers now collect more data than ever, but they may lack the time or expertise to analyse and utilise it fully. This creates a demand for user-friendly analytics and decision support systems that can turn raw data into practical actions. Another challenge is data fragmentation and compatibility. While the state-run system in Estonia is well-integrated via X-Road, data silos still exist in the private sector, foreign solutions and cross-border data transfers. For example, the data collected by the tractors' on-board computers collect valuable information, yet the access to this data might be restricted, making it more difficult to use in other

[55] For further information please refer to link.

applications[56]. This calls for open standards and agreements so that different platforms can share data between each other. Moreover, as digital systems handle sensitive farm and personal data, cybersecurity and data privacy remain ongoing concerns. Estonia addresses this through the use of its secure digital ID and X-Road's encrypted exchanges, yet constant vigilance is required to maintain trust. Furthermore, the national digital ecosystem requires significant effort to maintain, and to constantly update to today's standards. This requires a significant dedication and resource mobilisation from the government's side.

4.1.4 Lessons learnt

- **Building a digital foundation is mandatory and supports building trust in digital services:** According to the interviews and based on the literature review, it is fair to say that a key lesson is the importance of investing in core e-government infrastructure. Estonia's success was underpinned by early adoption of digital IDs for citizens, and the creation of the X-Road data exchange network. These enabled interoperability and trust across systems. A secure way to identify users online and a platform for different databases to communicate is a foundation that allows agricultural applications to connect to databases, avoiding data silos and duplicated efforts.
- **Interoperability and the "once-only" principle reduce efforts:** Aligned with the findings of the assessment and literature review, digital agriculture works best when systems are integrated. Estonia ensured that its land registry, farm animal registry, support payment system, and other databases could share data automatically. Farmers never have to enter the same information twice. Once the government has a piece of information (e.g. field boundary or animal ID), all services draw on the single source. This drastically cuts paperwork and errors. Adopting open data standards and APIs is crucial for such integration. Furthermore, interoperability not only saves time, but also lets authorities cross-verify information instantly, improving accuracy and trust.
- **User-centric design increases the uptake of digital tools and facilitates the spread of digital solutions:** Estonia's digital tools were developed with the end-users in mind. Interfaces such as the ARIB portal consolidated many functions in one place to simplify the user experience. Feedback from farmers was takin into account to ensure the system meets their needs, highlighting the importance of stakeholder consultation when developing such systems. Crucially, extensive training and outreach accompanied new e-services, ensuring that even less tech-savvy farmers could learn how to use them. User-friendly design, helpdesk support and demonstration of clear benefits are important to drive adoption. When farmers see quick wins such as faster payments or less hassle, they become advocates for using digital approaches.
- **Digitalisation reduces bureaucracy and simultaneously makes administrative producers easier and faster:** According to the interviews and literature review, a major benefit for Estonians was reducing the time required for bureaucratic processes. Simplifying regulatory processes via digital tech (e.g. prefilling forms with existing data, auto-notifying farmers of obligations) can make agricultural policies more efficient and farmer-friendly. Estonia demonstrates that even with complex EU CAP procedures, they can be streamlined through e-governance for the benefit of the farmers.
- **Data access and ownership are essential to build trust:** digital agriculture generates a lot of data, and the Estonian case study illustrates the importance of who can access and use that information. Farmers shall remain in full control of their data and shall be able to easily retrieve and transfer it as they see fit. Policymakers must ensure that data does not get locked in by proprietary platforms. Estonia uses open APIs and its stance that farmers can download or share their own records is a good practice. This empowers farmers with flexibility and encourages an innovative ecosystem of tools that can plug into core databases without restrictions.

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[56] For further information please refer to link.

- **The combination of technology with advisory support helps the uptake of digital tools:** As it emerged during the interview, most likely, Estonia would have not reached the level of digitalisation and uptake of digital technologies without strong guidance, continuous support and advice on the use of digital tools. Furthermore, farmers often need support in interpreting data and adjusting their practices accordingly. Estonia has strong agricultural advisory services and farmer organisations that have helped train users on new e-tools and shared best practices. Providing digital literacy programs in agricultural areas (e.g. rural areas), integrating decision support systems to help analyse data, and maintaining personal advisory services alongside e-services ensure that even smallholders and older farmers are not left behind. This, combined approach helps translate digital information into real productivity gains on the ground.

4.2 Case study from Romania

4.2.1 Context

The agriculture sector plays a significant role in the Romanian economy. Representing over 3.3% of the country's GDP in 2024. In terms of Gross Added Value, the sector was valued at EUR 7.9 billion in 2013, making up 3.6% of the nation's comprehensive GVA. Following a 10-year transformation, by 2023 the agriculture, fishing and forestry sector was valued at 12.6 billion and represented 4.2% of the comprehensive GVA of the economy, far outweighing the EU average of 1.8% and exhibiting significant growth[32].

In the period between 2010 and 2020, the number of farms has decreased drastically from 3 859 040 to 2 887 070, while there has been a notable increase in the average farm size from 3.4 to 4.4 hectares, resulting in reasonably stable areas of agricultural land throughout Romania. Furthermore, the country is particularly strong in arable land production, representing over 8% of the European Union's arable land area[57]. In 2022, arable land made up 65.2% of agricultural land in the nation, while Permanent grassland and meadows (32.4%) also play a significant role in agricultural production–permanent crops represented just 2.4% of total agricultural land. Romania's crop products account for 2.4% of member states' comprehensive crop products and is predominantly driven by agricultural outputs like cereals (including seeds) (EUR 3.9 billion), vegetables and horticultural products (EUR 2.8 billion) and fruits (EUR 1.5 billion). On the other hand, Romania's animal products, stemming from livestock, make up 1.2% of the EU's total animal products. Specifically, the nation's main animal product is pigs (EUR 917 million) and poultry (EUR 879 million), while animal related products like milk (EUR 1.6 billion) and eggs (EUR 1.2 billion) also play notable roles in the economy. In 2020, Romania's livestock units were 4 385 970, showcasing a decrease of close to 1 million LSUs compared to 2010, while the density of livestock remained unchanged in the period[58]– potentially indicating that livestock related agricultural land has decreased proportionately to the decrease in livestock units in the period[59].

In 2024, the agricultural sector has achieved an entrepreneurial income of EUR 2.6 billion, although it is crucial to note that incomes have been following a marginally decreasing path since their heights in 2021. The agricultural sector plays a significant role in the country's exports as well. The volume of exported agricultural products was EUR 11 billion in 2022, however, the imported volume was EUR 13 billion– resulting in an EUR 2 billion negative trade balance. Since 2015, Romania's agricultural product-related trade balance has been consistently negative, ranging between EUR -46 million and -2 billion. In 2022, commodities were the main driver of Romania's agricultural exports (EUR 7.5 billion), while main import factors were also commodities (EUR 6.5 billion), other primary products (EUR 3.3 billion) and Food preparations (EUR 2.6 billion)[44].

The agricultural sector serves as a major source of employment across the nation, in 2024, the sector employed 1 728 950 persons on average. Thus, the rate of agriculture-related employment of 20% far outweighs the EU average of 4%. However, there are also challenges that hinder the tapping of potential in the sector. The level of digitalisation in the sector remains modest, and the use of digital technology is lower than the EU average in the country[60].

Furthermore, the agricultural landscape is fragmented in the country. Most small farms are family-run, and Romania has the highest number of farmers in the EU. Additionally, 44% of the farmers are over 65 years old, and youth participation is relatively low in the country.

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57 Eurostat: Agri-environmental indicator - cropping patterns. Accessed at link.

58 European Commission: Analytical Factsheet – Romania. Accessed at link.

59 The livestock density index measures the stock of animals (cattle, sheep, goats, pigs, poultry and rabbits) converted into LSUs per hectare of utilised agricultural area.

60 Butu et al (2024): Romania's rural digital transformation and implications for agriculture. Accessed at link.

4.2.2 Specific context

Romania has a strong potential in agricultural in Europe in terms of total utilised agricultural area, having 12.7 million hectares of land dedicated to agriculture[61]. The country represents over 2.4% of crop production, and 1.2% of the total EU production of livestock.

The Romanian agriculture sector has the highest number of farms in the EU, yet 90% of these are small, family-owned and subsidised farms under 5 hectares[62]. A highly polarised structure also means that a handful of large commercial farms coexist with millions of smallholders. In 2016, over half of the Romanian farms operated on less than 1 hectare and together those accounted for around 5% of the country's UAA, whereas larger operations (over 50 hectares) accounting for about 0.5% of the farms controlled more than half of all farmlands[63]. This, combined with an aging farmer population (over 44% of Romanian farmers are above 65 years old[64]), set the stage for a slow initial adoption of digital innovations.

4.2.3 Digital Transformation in Agriculture

Over the last 15 years, however, the Romanian crop farming has gradually begun to utilise digital tools and precision agriculture technologies. Precision farming systems, such as GPS-guided tractors, yield monitors, and variable-rate application equipment have been witnessed an uptake of Romanian farms. The use of satellite imagery and remote sensing has been increasing to monitor crop development, soil moisture, and vegetation health across fields. A growing number of farms have started using IoT sensors e.g. soil moisture proves, weather stations and nutrient sensors, to gather real-time information on field conditions.

During the early 2010s, digital farming in Romania was low[65]. A few progressive farm enterprises started experimenting with precision agriculture tools, often as part of equipment upgrades. GPS-guided tractors with yield monitors made tentative inroads on larger arable farms, usually those with the capital to invest in modern machinery. Prior to the 2010s, effectively zero Romanian farms were digitised, any by 2015 around 6% of farms had adopted any form of digital technology in the farm[66]. At the same time, connectivity and digital infrastructure were also lacking during this period. In 2014, only 41% of Romania's rural population had internet access which limited the uptake of digital technologies[67].

Internet access had doubled by 2023, as 88% of households in the countryside had access to internet. This improved connectivity provided a crucial foundation for digital agriculture, as farmers could connect devices, use smartphone apps in the field, and tap into online platforms. Secondly, decreasing costs and wider availability of technology made digital tools more accessible. The price of GPS receivers, sensors and drones readily decreased, and free resources (e.g. The European Sentinel satellite imagery) became available for crop monitoring. Farmers increasingly use satellite imagery to monitor

[61] According to Eurostat, Romania ranks the 6th in terms of total UAA in Europe, following France (28.6 million), Spain (24.9 million), Germany (16.6 million), Poland (14.6 million) and Italy (13 million).

[62] European Commission: Romania – CAP Strategic Plan. Accessed at link.

[63] According to local news. Accessed at link.

[64] European Commission: Romania – CAP Strategic Plan. Accessed at link.

[65] Fertu et al (2019): Precision Agriculture in Romania: Facts and Statistics. Accessed at link.

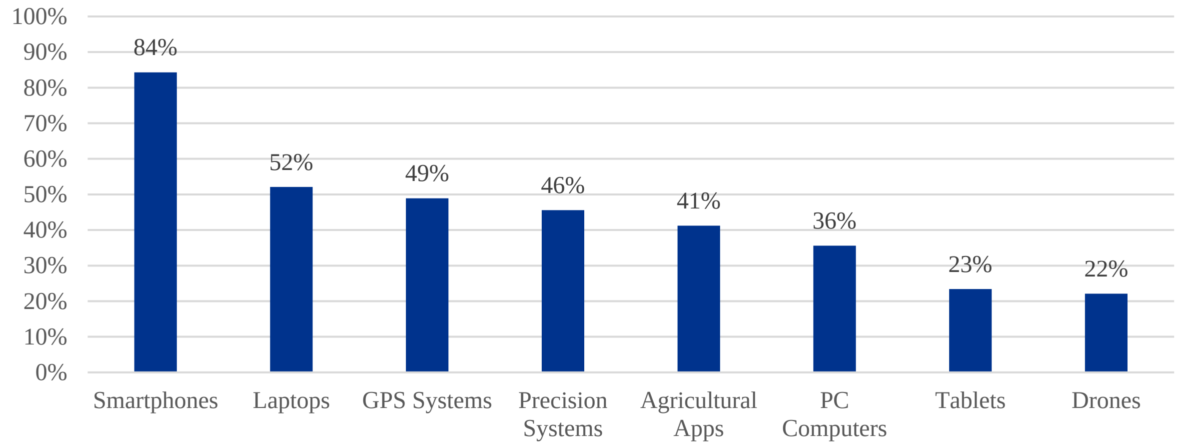
[66] Clubul Fermierilor Romani: Program Naitional pentru Digitalizarea. Accessed at link.

[67] Butu et al (2024): Romania's rural digital transformation and implications for agriculture. Accessed at link.

crop health, estimate biomass, and detect issues such as drought, stress or pest outbreaks across fields. Modern management platforms integrate such imagery to support decision-making (e.g. Agricover's Crop 360 platform allows farmers to visualise geospatial data for their plots imported from government registries, alongside up-to-date satellite images and weather data). The high-resolution images enable precision in applying inputs by monitoring vegetation index. Alongside satellites, some farms employ drones for remote sensing and croup scouting.

Another pillar of digital agriculture is **precision farming equipment and IoT sensors**. Many Romanian crop farmers who have modernised their tractor fleets now use GPS-based auto-steering and section control systems to reduce overlap in field operations. These systems ensure, for instance, that when spraying or seeding, every pass is optimally aligned, saving fuel and inputs. Yield monitors and GPS yield mapping on combines have allowed the first wave of data-driven decisions as farmers can quantify how different parts of their fields perform. In combination with soil sensors and grid soil sampling (services offered by agronomy companies), farmers can create variable-rate fertilisation maps. While fully automated variable rate technology (VRT) is still limited, a number of larger Romanian farms have adopted it to apply fertilisers and lime differentially based on soil needs, improving efficiency. Indeed, adoption of precision farming technologies has accelerated: the precision agriculture adoption rate in **Romania rose from around 5% of farms in 2020 to roughly 22% by 2025**[68], while it still **lags behind the EU average** which grew from 20% to 45% during the same period. The increasing availability and affordability of tools such as drones, GPS, sensors have been a driver of this increase. According to a survey conducted between 2020 and 2022[69], the use of GPS and precision farming system had increased significantly since the early 2010s. Almost half of the farmers utilise GPS (48.9%) and a significant portion use precision farming system (45.6%). More than a third of farmers use specialised farming applications (41.2%) while the use of drones remains significantly lower (22.1%).

Figure 6: Adoption rates of different technologies in Romanian farms, 2022



Source: Marius et al (2025). KPMG's design.

The rise of the utilisation of farm management software and integrated digital platforms tailored for agriculture is another trend in Romania. During the early 2010s, only a handful of farmers used any software beyond basic spreadsheets and most recording keeping was paper based. A survey of crop farmers revealed that while 75% of farmers use smartphones daily, which indicated that farmers are comfortable with mobile technology, yet only about 17% were using farm management software or apps to run their farms[70]. Almost half of the surveyed farmers still rely on notebook (49.5% of farmers) or

[68] Serban et al (2025): Digitalization of Agriculture in Romania Potential, Challenges and Comparative Analysis. Accessed at link.

[69] Marius et al (2025): Digital Technologies on the Farm: from the Improvement of Management Practices and Human Resources to Sustainability. Accessed at link.

[70] According to local news. Accessed at link.

Excel sheets (20%) for tracking fields and works, and 13.5% of them felt there is no need for digital tools at all. On the other hand, however, local agri-tech companies have sprung up offering user-friendly farm management solutions, often cloud-based and mobile friendly. Agriso, for example, became a leading provider of farm management and monitoring software in the local market. Another local example is Agricover's Crop360 platform which has a userbase of around 1 000 farmers, managing over 250 000 hectares of farmland on the platform[71]. **This underscores the importance of localised and farmer-centric solutions which can effectively support farmers to digitise their processes**.

The use of national and EU funds, and policy incentives has played a role in increased adoption of digital technologies among Romanian farmers. EU funds under the Common Agricultural Policy (CAP) have provided substantial support for farm modernisation. Through the National Rural Development Programme (NRDP) 2014-2020, Romania offered investment grants to farms for purchasing new machinery and equipment, which implicitly included precision agricultural machinery (e.g. modern tractors with GPS, advanced sprayers etc.). Direct payments under the Pillar I of the CAP have supported farmers with capital to reinvest in technology. However, it shall be mentioned that during the 2014-2020 programming period, medium and larger farms may had benefited more from direct payments under Pillar I due to its inherent structure[72]. In the current CAP (2021-2027), the EU has put more emphasis on digital innovation in agriculture, which entails that Romania's CAP Strategic Plan acknowledges the need to support precision farming and farm digitalisation. For instance, the plan sets the results indicator (R.3) to measure farmers benefitting from support for digital farming technology. Beyond direct funding, policy initiatives and partnerships have also played a role. Romania joined the EU Declaration on "A Smart and Sustainable Digital Future for European Agriculture" in 2019, signalling high-level commitment to digitalising the sector. The country also has established Digital Innovation Hubs focusing on agriculture, e.g. the Transylvania Digital Innovation Hub[73] that provides training, test facilities and advisory for agri-tech startups and farmers. These hubs aim to act as one-stop shops for farmers seeking to adopt digital solutions. To further strengthen the high-level commitment to digitalisation, the Ministry of Agriculture and Rural Development of Romania has developed the Smart Agricultural Strategy (as part of the broader Digital Agenda) emphasising the development of the digital transformation of the sector. Furthermore, Romania has strengthened its Agricultural Knowledge and Innovation System (AKIS) in the current plan by allocating funds and resources for farm advisors and training programmes.

The adoption of digital technologies can support farmers in enhancing productivity and profits in a competitive sector. While the agricultural sector is significant in Romania, the exposure to Western farming standards (many Romanian farmers export their goods to Western Europe) require the sector to improve as well. By the late 2010s, it became clear that traditional farming methods were limiting yield potentials as it only reached about 38% of the EU average labour productivity in agriculture by 2023[74]. **Farmers who have adopted digital tools report tangible benefits, yields and input efficiency are key highlights**. According to studies and stakeholder interviews, Romanian farms using precision agriculture techniques have seen improvements in crop yields and resource efficiency while reducing environmental impacts. Site-specific input management means fertilisers and pesticides can be applied only where needed, in optimal amounts, boosting productivity per unit while cutting waste and runoff. On a large maize farm in the south, for example, adopting GPS-guided variable fertilisation and keeping digital yield maps has translated into higher average yields and more uniform crops, as the farmer can

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[71] According to Agricover. For further information please refer to link.

[72] Under the Pillar I of CAP during the 2014-2020 programming period, the direct payments were area-based, meaning payments were calculated per hectare of eligible lands. Important to note that capping and redistributive measures were introduced and those had redistributive effects to a varying extent.

[73] For further information please refer to link.

[74] According to local news. For further information please refer to link.

address low-fertility spots identified by data[75]. With real-time data (from sensors or satellite imagery) at hand, farmers can make quicker, better-informed decisions such as identifying a disease outbreak in one field via a drone survey and promptly targeting that area for treatment. **Digital record-keeping also helps with compliance and accessing markets**. Traceability systems and digital farm logs can open doors to certifications or premium buyers looking for sustainability data. The synergy between technology and agronomic knowledge has started to create a more **resilient farming system**. Many Romanian farms that use digital tools feel better equipped to adapt to challenges like climate variability, because they can monitor micro-climate data on their fields and adjust practices accordingly. While these success stories are mostly among larger players, they set important examples nationally.

The digitisation of Romanian agriculture carries significant social implications as well. On the one hand, it can offer new opportunities to revitalise rural areas and change the nature of agricultural work. The introduction of digital tools is beginning to reduce the drudgery of farming, which essentially can lead to better working conditions for farmers. Also, it can compensate for the declining rural labour force and make the sector more appealing by increased working conditions for agricultural workers. Romania has one of the highest shares of population employed in agriculture, yet this figure has been declining as younger generations leave for other sectors. By adopting automation and data-driven methods, farms can maintain or even increase output with fewer workers. Advanced machinery and data analytics help farmers to "do more with less", increasing productivity measures on the farms. In this sense, digitalisation can sustain farm viability and incomes even as rural demographics change. It also can raise the skill level of agricultural employment as demand has been growing for technicians who can operate drones or agronomists who can interpret software output, potentially creating more skilled jobs in rural areas. Furthermore, as mentioned before, it creates new entry opportunity for tech-savvy companies to enter the agricultural sector by providing hands-on solutions for farmers.

Despite this progress, Romania's agriculture in 2025 is still only partially digitised. The majority of farmers, especially smallholders, have yet to adopt advanced tools. As noted, a **digital divide** is evident. On one side are the commercial farms (often over 50 or 100 hectares) that are increasingly high-tech; on the other side are millions of small farms that remain analogue and labour-intensive. The social and structural barriers underlying this divide are significant. **Key barriers and challenges** have continually impeded the widespread implementation of digital technologies across Romanian agriculture. One fundamental challenge is the **lack of awareness and digital literacy**. A large share of farmers, particularly older and small-scale ones, are not fully aware of the potential benefits of digitisation, or simply do not feel it is relevant to their scale of operation[76]. This ties closely to education gaps, as about 98% of farmers in Romania have gained their skills solely through hand-on experience on farm, while under 2% having any formal training in agriculture, let alone digital tools[77]. In contrast, in some Western European countries over half of the farmers have at least basic agricultural training, which often includes exposure to modern technologies. Another risk is the increasing **inequality between farmers**. Larger, wealthier farms are rapidly advancing, potentially widening the productivity gap with smallholders. This could entrench a two-speed agriculture unless measures (like cooperative approaches or subsidies for small farm tech) are taken to spread the benefits. There is also the psychological barrier as some farmers may feel a loss of traditional knowledge's value in the face of algorithm-driven recommendations. It can be intimidating to trust "black box" software suggestions over one's own experience. Overcoming this reluctance is partly a generational issue and partly a matter of building user-friendly tools that complement, rather than override, farmers' intuition.

[75] M. Butu, V. Dragomir (2024): Comparative analysis of precision and digital agriculture adoption in Romania and Western Europe. Accessed at link.

[76] Rodino et al (2023): Challenges of digital transformation in agriculture from Romania. Accessed at link.

[77] Autoritatea pentru Digitalizarea României (2023): Raport de analiză a practicilor și politicilor relevante în domeniul European. Accessed at link.

4.2.4 Lessons learnt

- **Farm structure matters immensely for digital uptake:** Romania has many smallholder farmers with limited capital, and they cannot readily adopt expensive precision tools, whereas larger farmers can. This entails that not only technologies, but policies (e.g. subsidies) must be tailored for smallholders.
- **Economic and social sustainability must be balanced:** A reflective insight from Romania is the double-edged sword of automation on rural communities. While farm efficiency improves, rural employment may diminish and change. This is why it is important that digital agricultural strategies and programmes are integrated with rural development policies.
- **The high-level political recognition and dedication is essential to boost the uptake of digital technologies.** The high-level commitment to digitalisation supports the alignment of supporting schemes (e.g. CAP) to the broader goals and shapes the digital landscape of digital agriculture. Romania has developed the Smart Agricultural Strategy as part of a broader Digital Agenda and has strengthened the role of AKIS.

4.3 Case study from Germany

4.3.1 Context

The German agricultural industry is the 2nd biggest by volume in the European Union. The gross value added of the agricultural industry at basic prices was around EUR 75.5 billion in 2024, which represented over 14% of the European Union's total agricultural output in the same year. The agricultural sector accounted for 0.9% of the country's GDP in 2024, while it employed around 700 000 people in the same year. Germany's agricultural sector has exhibited strong economic resilience and sustainability, achieving entrepreneurial incomes ranging from EUR 8.0 and 15.9 billion between 2019 and 2024. Both crop production and livestock production are significant in the country and accounted almost equally for agricultural outputs in 2024[78].

In terms of crop production in the EU27, Germany ranked the 4th in 2024 with over EUR 31.1 billion (around 13% of the total EU volume). Moreover, the country holds over 16.5 million hectares utilised agricultural area (UAA), which accounts for 10.5% of the total UAA of the European Union[79]. Of the utilised agricultural area found in the country, 70% is arable, 29% serves as permanent grassland and meadows, while just 1% is utilised for permanent crops. In terms of crop products, Germany is particularly effective in the segments of vegetables and horticultural products (EUR 8.5 billion), cereals (including seeds) (EUR 6.8 billion) and industrial crops (EUR 6.3 billion)[45].

In terms of livestock production, Germany was the 1st in 2024 with over EUR 36 billion at basic price in 2024, which represented around 16.7% of the total livestock output in the same year. Namely, Germany's notable animal products include pigs (EUR 8.4 billion) and cattle (EUR 4.8 billion), alongside related dairy products (EUR 15.4 billion). Furthermore, Germany ranks 3rd in terms of livestock units (LSU) with over 16.2 million units, following France (19 million) and Spain (16.6 million)[80]. Despite being at the forefront of European agricultural production capabilities, Germany remains a net importer of agricultural products– achieving a trade balance of EUR -18.9 billion in 2024[45].

The agricultural sector employed around 572 000 people in 2023, representing around 1.3% of the total employment in the country[81]. Around 7% of the farmers were below the age of 35 in Germany, which is slightly higher than the EU average of 6.5%[82]. At the same time, around 40% of the farmers were above the age of 55[83].

4.3.2 Specific context

Organic agricultural production is significant in Germany, possessing 9.7% of the EU's total organic area. In the period between 2012 and 2022, the nation's total organic area grew by 70%, reaching 1 630 984 hectares by the end of the period. Thus, 9.8% of the total utilised agricultural area (UAA) was fully converted or under conversion into an organic area, marginally falling behind the EU average of 10.5%. Of the comprehensive organic designation agricultural areas, 47.7% is arable land, 50.8% is permanent grassland, while 1.6% is for permanent crops. Germany is one of the European leaders in the

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[78] The crop output in the country accounted for around 49.8% of the total agricultural output in 2024, while animal production accounted for 50.2%. Expressed in million EUR. Based on Analytical Factsheet – Germany (2025). For further information please refer to link.

[79] Based on Eurostat: Main farmland use by NUTS2 region. Accessed at link.

[80] Based on Eurostat: Main livestock indicators by NUTS2 region. Accessed at link.

[81] Based on EURES: Labour Market Information: Germany. Accessed at link.

[82] Eurostat: Farmers and the agricultural labour force – statistics. Accessed at link.

[83] European Commission: Germany – CAP Strategic Plan. Accessed at link.

share of organic fresh vegetable in total vegetable production, wherein 10.4% of the segment stem from organic practices, falling only behind Sweden's elevated efforts.

On the other hand, in terms of livestock, on a weighted average basis, just 4.4% of animals were kept under organic agricultural practices in 2022, although a wide discrepancy can be observed by animal type. Namely, organic practices in relation to pigs– the most numerous animal category in Germany– are limited (0.8%), while in the case of dairy cows, bovine, sheep and goats, the range of organic practices were between 6.8% and 32.3%[84].

Products stemming from organic agricultural practices also play a significant role in the economic success of the sector. Namely, in 2022, organic retail sales were valued at EUR 15.3 billion, the highest of any of the member states. At the same time, organic retail sales had a national market share of 6.3%, which while higher than the EU average, was significantly lower than European leaders of the segment like Denmark (12% market share)[85].

4.3.3 Digital Transformation in Agriculture

Germany is ranked among Europe's leaders in using digital technologies to reduce GHG emissions[86], and in the last decade, organic farmers in Germany have been increasingly embraced digital technologies to enhance sustainability and efficiency on their farms. Digital tools support organic farmers in cutting GHG emissions by optimising resource usage, such as sensor-guided decision systems, which can fine-tune fertilisation and irrigation so that crops get the required volume of agricultural inputs. This effectively reduces excess nitrogen (and, thus, nitrous oxide emissions), and leads to fuel saving from less machinery usage. In practice, digital technologies align with organic farming's eco-friendly approaches via utilising data to apply only the necessary inputs which entails lower emissions and healthier soils. Even though organic farms avoid synthetic fertilisers, they still can benefit from tools such as soil sensors and crop apps that help apply organic manures or plan cover crops just at the right time, preventing GHG release from over-application.

Across Germany's organic crop field, orchards, vegetable plots and livestock, farmers find practical ways to integrate digital tools into daily operations. **In organic crop production**, precision agriculture techniques are being adopted to organic needs. **Drones and remote sensor** monitor fields to detect pest outbreaks or nutrient deficiencies early, allowing farmers to respond proactively to specific areas and / or concerns, without heavy chemical sprays. **Tractors equipped with steering systems** enable more precise operation on a field level, reducing the use of energy for machinery by enhanced end-of-table turn-arounds and improved tracking. Weeding robots, and small autonomous machines, such as FarmDroid robots[87], navigate between crop rows to identify weeds either via camera or pre-programmed GPS coordinates, and eliminate them mechanically, thus avoiding the use of herbicides for weed control. **Another key area is irrigation**. While farmers benefit from efficient water use, it is especially valuable for organic horticulture, where water stress can make plants more susceptible to pests. IoT-based irrigation systems allow organic vegetable and fruit farms to deliver water exactly in the volume it is needed, using moisture sensors and weather data. Water-use efficiency can be improved by 25-50% with smart irrigation systems, often leading to enhanced crop yields and increased resistance of plants. In fruit cultivation, orchardists use smartphone **apps and sensor networks** to monitor microclimates and predict diseases (e.g. warning systems for organic apples that alert growers of an

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[84] Eurostat: Developments in organic farming. Accessed at link.

[85] OrganicTargets4EU: Germany Organic Sector Factsheet. Accessed at link.

[86] Krachunova et al (2025): Digital technologies commercially available in Germany in the context of nature conservation and ecosystem service provisioning in agriculture. In Frontiers in Sustainable Food Systems, Sec. Agroecology and Ecosystem Services. Volume 9. Accessed at link.

[87] For further information please refer to link.

approaching risk of blight so they can apply organic treatments in time). **Organic livestock farmers** have started implementing digital tools as well. For example, organic dairy and beef producers use sensor **collars and smart tags** to monitor their animals' health and grazing patterns. These devices can send alerts if a cow's activity drops (a sign of illness or calving) or if animals wander too far, helping farmers ensure high welfare standards with less manual checking. As it was mentioned during the stakeholder interviews as well, the less manual checks and the health monitoring significantly helps farmers to identify degrading health conditions of animals and allows remote monitoring freeing up significant time for the farmers that they can allocate for other activities[88]. It also enables more flexible and diverse employment models, allowing farmers and agricultural workers to engage in specialised tasks such as data analysis or remoting monitoring, which can attract younger, tech-savvy individuals to the agricultural sector.

Digital innovations continue to add value post-harvest as well. Organic grain and vegetable growers use **sorting machines with machine vision** to grade the quality of their products (enabling different pricing for different product quality), and **climate-controlled storage equipped with smart thermostats or CO2 sensors** keeping perishable organic produce fresh longer by maintaining ideal conditions. Furthermore, as it was mentioned during the interviews as well, many organic farmers have also started utilising **e-commerce and digital marketplaces as a natural extension of their farm operations** (such as Marktschwärmer in Germany). Selling and advertising organic products online, whether via farm websites, social media or dedicated platforms, allow farmers to reach consumers directly and coordinate sales efficiently[89]. In fact, **digital direct marketing** has become an essential tool for organic producers worldwide to improve their margins and reduce waste in the supply chain.

Digital tools can support obtaining organic certification in Germany. With over 36 000 certified organic farms[90] and a highly engaged consumer base, the demand for traceability, transparency and strict adherence to organic standards is explicitly high. German organic producers operate within the framework of EU Regional (EU) 2018/848[91], yet they are also subject to additional expectation from national labels such as the Bio-Siegel[92] and private certificates such as Bioland[93], Naturland[94] or Demeter[95]. In this environment, digital tools play an increasingly vital role in helping producers align with certification standards efficiently and in a credible manner. Digital farm management software (such as NEXT Farming, 365FarmNet, agrarOffice) enable farmers to track and document their operations in real time. For livestock producers, Germany's Hi-Tier System[96] registers animal movements and data nationwide and serves as a cornerstone of compliance. When integrated with farm-level digital tools, it allows real-time synchronisation with national databases, reducing the risk of non-compliance. Additionally, digital breeding records and integrated pasture monitoring apps can provide certifiers with clear, time-stamped evidence of adherence to organic animal welfare standards. Beyond

[88] According to a conducted in 2024, 69% of the farmers reported that digital applications saved time, and 61% of them reported improved efficiency in production. For further information please refer to link.

[89] The use of direct-to-consumer resulted in about 20% lower carbon emission and reduced food waste to 3% from 22%. For further information please refer to link.

[90] According to the Institute of Farm Economics: Organic farming in figures. Accessed at link.

[91] Regulation (EU) 2018/848 on organic production and labelling of organic products and repealing. Accessed at link.

[92] For further information, please refer to link.

[93] For further information, please refer to link.

[94] For further information, please refer to link.

[95] For further information, please refer to link.

[96] For further information, please refer to link.

individual farms, **blockchain-backed traceability platforms** (such as Trick[97] fTrace[98], Organic Garden and Yaliyomo[99]) are being piloted by German organic cooperatives to secure the integrity of high-value products such as organic cereals, honey, and dairy.

Despite benefits, organic producers do face some barriers as well when investing in digital technologies beyond the gaps in skills and digital literacy issues. Many organic farms are relatively small or highly diversified, which means the **return on an expensive precision-farming tool might be uncertain** due to some precision agriculture tools only becoming cost-effective at very large scales (in some cases, farms of 200–300 hectares or more are needed to justify certain technologies)[100]. This can put cutting-edge hardware out of reach for a typical organic farm in Germany, unless famers cooperate or find affordable, scaled-down solutions. On a positive note, however, according to the stakeholder interviews farmers have a higher tendency to cooperate between their peers, which strengthens their position in investing and using digital, and more advanced technologies. Furthermore, open-source solutions (such as AgOpenGPS[101]) offers cheaper solutions for farmers to get involved with precision agricultural solutions. Additionally, a **lot of digital farming technology has originally been developed with conventional farming in mind**, which can limit its immediate usefulness for organic farmers. For example, a standard decision-support software might recommend chemical pesticide or the use of synthetic fertiliser, options that organic farmers cannot use.

4.3.4 Lessons learnt

- **Organic farming as a pillar of sustainability can be strengthened by digital solutions:** Germany pushes towards organic agriculture which is not only driven by consumer demand but also by the recognition of organic's environmental benefits. Organic farming in Germany has expanded significantly and organic farming demonstrably contributes to climate mitigation (e.g. organic crop systems emit roughly half of GHG per hectare). Digital technologies reduce resource use and environmental impacts, whilst also increasing trust between producers and consumers via blockchain-based certification systems.
- **Economic, environmental and social benefits go hand in hand:** The German case study reveals that improvements in environmental performance often goes with economic and social benefits. Lower use of agricultural inputs saves money, while optimising herds or yields increases revenues. Furthermore, direct marketing and direct-to-consumer sales can increase farmers' income and, at the same time, result in shorter supply chains, essentially reducing GHG emissions from transportation. The application of digital tools also enables a more flexible and diverse employment model, where workers and farmers can engage in specialised tasks such as data analysis. This can attract younger generations to the agricultural sector as well.
- **Digitalisation should not be the goal but the mean:** The use of digital technologies alone will not automatically lead to better environmental results. The use and application of digital tools and technologies increases the electricity consumption on a farm level, which should be taken into account when assessing the GHG emission of the sector. However, if the goal is to reduce the GHG emission in the agricultural sector, the right and proficient selection, and use of digital technologies can support farmers to reduce their impact on the environment.

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[97] For further information please refer to link.

[98] For further information please refer to link.

[99] For further information please refer to link.

[100] Petrovic et al (2025): Adoption of drone, sensor, and robotic technologies in organic farming systems of Visegrad countries. Accessed at link.

[101] For further information please refer to link.

4.4 Case study from Spain

4.4.1 Context

Spain's primary sector plays a significant role within the European Union. In terms of gross value added (GVA) related to agriculture, forestry and fishing, Spain accounts for approx. 13.4% of the EU total. Domestically, the primary sector contributed 2.7% of Spain's GDP in 2023, well above the EU average of 1.8% in the same year. In nominal terms, this translated to EUR 37.5 billion, making Spain the third largest contributor to the European agricultural sector, following France and Italy[32].

Employment in the sector remains substantial. In 2024, an average of 764 600 people worked in the agricultural sector, representing around 3.5% of the total employment in the country[33]. Labour productivity in the sector experienced a strong 15% growth between 2010 and 2021, but has slightly declined over the past three years, now being slightly below the EU average.

Land use patterns in Spain have remained relatively stable over the last decade. Between 2010 and 2023, the total Utilised Agricultural Area (UAA) showed little overall change and stood at almost 24.9 million hectares in 2023[102]. While the number of farms slightly decreased, average farm sizes grew modestly, leading to stagnation in total agricultural area. This entails that farm consolidation slightly increased in the country in the last decade. Out of the UAA, 47.5% is arable land, 31.6% is permanent grassland and meadows, and 21.8% is used for permanent crops.

Crop production dominates Spain's agricultural output, accounting for 58.3% of the sector's total. Key products include vegetables and horticultural goods (19.5% of total output) and fruits (18.4%). Meanwhile, livestock production has also expanded, with number of livestock units (LSUs) growing at an average annual rate of 1.1% of the past decade, reaching 16.6 million LSUs in 2020. Animal products contribute 41.7% of the sector's output, led by pigs (16.6%), milk (7,5%), and cattle (7%)[103]. Livestock density in Spain has also increased to 0.7 LSU per hectare, aligning with the EU average[104].

Economically, the sector has shown strong performance over the past ten years, with entrepreneurial income ranging between EUR 18.1 and 23.2 billion annually. In 2024, a record year, the sector reached EUR 23.2 billion in entrepreneurial income. This was primarily driven by crop output (EUR 31.3 billion) an animal output (EUR 22.6 billion), while major cost components included agricultural inputs (EUR 16.7 billion) and other operational costs (EUR 11.1 billion). Spain also maintains a consistently positive agricultural trade balance. Between 2012 and 2022, the surplus ranged from EUR 8.8 to 21.1 billion annual, with export of other primary and processed products forming the backbone of this performance[41].

Due to Spain' varied climate, ranging from coastal zones along the Mediterranean and Atlantic to mountainous regions, and increasing incidents of drought, a reliable and efficient irrigation is essential for ensuring the long-term sustainability of its agricultural sector.

4.4.2 Specific context

Irrigation is fundamental to Spanish agriculture's output and resilience. Spain's climate, characterised by hot dry summers and irregular rainfalls in much of the country, highlights the crucial role of irrigation for high productivity. Although irrigated land accounts only for only about 22% of Spain's cultivated area (between 3.8 and 4 million hectares), it produces over 50% of the country's crop output by value. This entails that half of Spain's plant production comes from less than a quarter of the country's farmland, thanks to irrigation.

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[102] Eurostat: Utilised agricultural area by categories. Accessed at link.

[103] European Commission: Analytical Factsheet- Spain. Accessed at link

[104] Eurostat: Agri-environmental indicator. Accessed at link

Irrigation is the pillar supporting the fruit and vegetable sector's export potential. Spain is the EU's leading exporter of fruits and vegetables, and among the top three globally, reflecting the success of irrigated Mediterranean crops in meeting European market demand. Without irrigation, however, Spain most likely could not sustain its large citrus orchards, vegetable farms, olive groves, and vineyards at current output level, especially in the drier southern and eastern regions.

Irrigation is not only economically crucial, but also a major consumer of water resources in Spain. The agricultural sector accounts for roughly 82% of all freshwater usage nationally[105], primarily for irrigation purposes. This dominance means water policy and agriculture are deeply intertwined. Over the past few decades, Spain has undertaken continuous irrigation modernisation to improve water-use efficiency. Traditional flood irrigation has steadily given way to more efficient techniques such as drip and sprinkler irrigation. By 2021, drip irrigation had expanded to about 2.1 million hectares (more than half of the total irrigated land), while old gravity-fed methods fell to about 22%[106]. This shift has significantly increased water productivity, enabling farmers to produce more crop per water unit, which is a critical adaption in a country prone to drought. The modernisation of physical irrigation infrastructure sets the stage for the digitalisation of the irrigation management in the country. In recent years, Spain has increasingly focused on integrating digital tools in irrigation systems to optimise water use, energy efficiency, and crop performance in real time.

4.4.3 Digital Transformation in Agriculture

Digitalisation of irrigation in Spain has accelerated as a strategic response to both productivity goals and environmental pressures. Notably, the Spanish government and EU have directed substantial funding to support high-tech irrigation. Spain is dedicated to increase the competitiveness of the agricultural sector. **A total of EUR 2.1 billion is to be invested into the modernisation of irrigation systems in Spain until the end of the 2021-2027 programming period**[107]. Among other funds, the Recovery Plan allocated EUR 563 million to the modernisation of irrigation systems, which represents over 53% of the total budget of the Recovery Plan, highlighting the importance of the modernisation of irrigation for the country. Additionally, a total of EUR 410 million of the NextGenerationEU funds included in the Agri-food Strategic Project for the Recovery and Economic Transformation (PERTE) are for actions in irrigation. Under the post-COVID Recovery Plan, Spain launched a plan for improving irrigation efficiency and sustainability, allocating EUR 563 million to modernise over 100 000 hectares of irrigated land with advanced technologies[108]. The modernisation projects prioritise installations that have an important innovative component, such as the incorporation of technologies and digital tools[109] in irrigation communities to achieve more efficient irrigation. In practical terms, this means adding sensors (such as weather, soil and moisture sensors), automation (such as irrigation scheduling and water flow controls), and data systems to existing irrigation networks.

The level of technological development in Spain's irrigation has been steadily rising. Many irrigated farms and water user associations now utilise some form of digital precision tools. For example, IoT-based sensor networks and automated irrigation controllers are increasingly common in advanced irrigation districts. These allow real-time monitoring of soil moisture, weather, and canal flow, and can

[105] Caixa Bank Research (2022): The use of water in agriculture: making progress in modernising irrigation and efficient water management. Accessed at link.

[106] Hoogesteger et al (2023): Imaginaries and the Commons: Insights From Irrigation Modernization in Valencia, Spain. In International Journal of the Commons. Vol. 17 Issue 1. Pp. 109-124. Accessed at link.

[107] According to the Government of Spain. Published at link.

[108] The Plan was launched under the Investment 1 of Component 3 of the Recovery, Transformation and Resilience Plan in Spain.

[109] Such as IoT-based sensor networks, automated irrigation controllers, and real-time monitoring devices.

automatically adjust watering schedules. A recent survey-based observatory of the agri-food sector[110] found that virtually all farmers now have basic internet access, and many are open to adopting digital solutions to improve margins and environmental outcomes. Precision agriculture applications, including precision irrigation, are among the most promising and widely adopted digital practices. Farmers are using tools such as remote sensing, smart irrigation scheduling apps, and GPS-guided equipment. Research identifies precision irrigation, field monitoring, and data-driven fertilisation as high impact areas, enabled by technologies such as cloud computing, IoT, robotics and AI.

Some regions in Spain have become innovation hotspots for digital irrigation. The arid southeast region, for instance, has pioneered tech solutions in response to the climatic conditions. **Murcia**, a region with scare water resources, is often cited as a leader in irrigation innovation. One of the solutions stemming from this region is Smart Agri system, which was implemented to let farmers monitor and control their plot's irrigation remotely via smartphone or computer. This low-cost **LoRaWAN-based[111] network connects micro-plots, valves, and meters to enable farmers to precisely manage water without being physically present[112]**. Other regions have also showed advancement in digitalisation. For example, in the regions of **Aragon** and **Catalonia** modernisation projects are being implemented focusing on digital water management integrating telemetry and renewable energy into traditional canal systems. The Demofarm project from **Andalusia** aimed to apply digital solutions on a farm level, including **AI tools for irrigation scheduling in olive groves[113]**.

In the last couple of years, a number of projects were supported in the framework of HORIZON 2020 of the EU in the Spanish irrigation. For example, the Spanish company Galpargo developed a regulated deification irrigation (RDI) protocol for olive trees. This estimates the water needs of olive plants and reduces irrigation to the minimum necessary level. The EU-funded HydSOS project[114] aimed to develop a sensor that continuously estimates the olive tree's water potential, permit the replacement of previous techniques. The sensors allow the effective application of the RDI protocol in olive trees with aims to extend the use to other plants as well. Similarly, the SWAMP project[115] aimed to develop IoT based methods and approaches for smart water management in precision irrigation domain. The project was piloted in Brazil, Italy and Spain to create an advanced system to integrate the water distribution and water consumption in the same decision-making system that helps farmers to eliminate the waste of water typically in large-scale water distribution networks in rural areas. This was achieved by creating a smart water management platform for precision irrigation based on advanced IoT and semantic web concepts.

The increasing use of digital irrigation technologies has begun to yield tangible benefits. Farmers and officials report improvement in water-use efficiency, as **sensor-driven irrigation avoids over-watering and reduces water losses**. Studies note that converting to modern irrigation, such as the combination of drip irrigation systems managed by digital control, can cut water usage significantly while maintaining or even increasing yields. Enhanced monitoring also helps save energy, for example by scheduling pumping when renewable energy is available or by reducing excess irrigation that wastes pump energy. Economic gains include higher yields and productivity. Additionally, digital record-keeping of water use helps improve compliance and resource governance, which is vital in a country where water is tightly regulated. On a strategic level, digitalising irrigation is seen as essential for climate

[110] The survey was conducted of the Ministry of Agriculture, Fisheries and Food of the Netherlands. The survey was conducted from July to November in 2022. The results were published in September 2023. For further information please refer to link.

[111] LoRaWAN refers to low-power wide-area network protocol that enables secure and dependable bi-directional IoT communication.

[112] Chazarra et al (2020): Adaption of a Traditional Irrigation System of Micro-Plots to Smart Agri Development: A Case Study in Murcia (Spain). Accessed at link.

[113] For further information please refer to link.

[114] For further information please refer to link.

[115] For further information please refer to link.

change adaption. With droughts becoming more frequent, smarter irrigation systems allow agriculture to be more resilient to water stress by optimising every drop and enabling the use of non-conventional water sources (such as reclaimed wastewater or desalinated water).

Despite clear benefits, the adoption of digital tools in irrigation faces challenges. As for all digital technologies**, the high upfront costs and financing limitations remain one of the main barriers** of adoption. Farmers, especially smallholders, may be deterred by the capital requirement for such investments. While public subsidies are available, according to a survey conducted in 2022[116], half of the farmers were unaware of governmental digitalisation grants such as the "Digital Kit" programme. This underscores the gap in outreach and support awareness in the country. Additionally, **the uncertainty regarding the return on investments remain another challenge**. While farmers seem to acknowledge the potential productivity improvements, there is a caution about the reliability and profitability of new systems. Until more success stories show clear increase in farm revenues or substantial costs saving, adoption may be hindered among risk-averse farmers. **Digital skill gaps among farmers and farm workers further hinders the adoption**. The older generation of farmers may be less comfortable with new technologies, while the survey[117] highlights a strong demand for trainings. However, these training sessions must be adopted to farmers' needs. Short, straight to the point and specific training modules in specific agri-tech usage can be more benefiting for farmers and farmworkers.

4.4.4 Lessons learnt

The Spanish experience with digitalising irrigation over the past several years provides a number of key lessons and insights.

- **The recognition of strategic importance of digital irrigation strengthens the uptake of digital tools:** modernising the irrigation with digital technologies is not optional but necessary due to the climate change induced effects, especially in the case of southern countries. Spain has recognised the importance of adapting irrigation infrastructure with smart controls, monitoring and better water allocation, to ensure the sector's long-term sustainability and resilience. Digital tools can substantially improve water efficiency, enabling farmers to "do more with less" water.
- **The combination of public investments and policy support is essential to increase the use of digital technologies:** the robust public support has been a catalyst for Spain's irrigation digitalisation. The infusion of EU and national funds targeting irrigation modernisation lowered the financial barriers for many irrigation communities to adopt new technologies. The public-private partnership is essential to ensure that the funds generate the most impact possible, and the governmental support ensures that farmers can adopt the technologies that they may not be able to alone.
- **The recognition of the importance of human capacity and awareness are critical:** as it was highlighted during the interviews and noted by the literature review as well, technology alone is not enough to generate change, training and awareness raising campaigns are essential. Despite available programmes, half of the farmers were not aware of funding opportunities, hindering the adoption of such technologies. Furthermore, investing in trainings, education and advisory services (including pilot farm demonstrations) seems to be as important as investing in hardware.
- **Demonstrating value to farmers can showcase the hands-on benefits for farmers:** adoption can scale when farmers clearly see their return on investments and practical benefits.

[116] The survey was conducted of the Ministry of Agriculture, Fisheries and Food of the Netherlands. The survey was conducted from July to November in 2022. The results were published in September 2023. For further information please refer to link.

[117] Ibid.

Demonstrative pilots, actual success examples can convince farmers to adopt digital technologies in order to increase yield gains, cost savings or reduce risks. Real-world examples and case studies help convince sceptical stakeholders. Transparent monitoring of outcomes should be part of each demonstrative project as well.

- **One solution does not fit all, so there is a need for a holistic and context-specific approach:** digital transformation in agriculture is uneven. This entails that one-size fits all approach does not work in case of digitalising the agricultural sector. Knowledge exchange between regions, and farmer-centric solutions can increase the uptake of digital technologies. However, holistic planning is essential on a country level. Combining infrastructure upgrades, training, financing and environmental safeguards yields the best results. The Spanish example demonstrates that digitalisation in the sector is a continuous journey. It involves the deployment of hardware and software solutions, alongside with trainings, environmental considerations, water governance policies and farm management practices.

5. Policy-oriented recommendations

The findings from the assessment of the environmental, social and economic impacts, and the country-specific case studies covering four EU Member States, offer a comprehensive picture of both the opportunities and challenges associated with digital transformation in the sector. Based on these findings, the following policy recommendations aim to address the most pressing needs identified during the study. The recommendations are intended to support more inclusive, sustainable and effective digital transitions, and to provide a guidance for policymakers in designing targeted interventions.

I. **Establish and strengthen a dual investment approach targeting rural digital infrastructure**. Rural digital infrastructure needs to be expanded and modernised by prioritising broadband services, especially in uncovered rural and remote areas. This should be achieved through public-private partnerships and by utilising targeted funds e.g. EU Cohesion Policy funds (Cohesion Funds and European Regional Development Funds), Connecting Europe Facility (CEF). At the same time, digital innovation grants and co-financing schemes under the CAP or national development programmes need to be supporting farmers in acquiring and implementing digital tools.

II. **Combine and promote synergistic investment incentives in digital technologies and renewable energy systems**. To enhance resilience, sustainability and competitiveness of the agricultural sector, rural investment policies should support integrated investment packages, that combine the uptake of digital technologies with on-site renewable energy generation. By linking green and digital transition at farm level, the investments can contribute to the EU climate goals, strengthen food system resilience, and contribute to net-zero greenhouse gas emission of the agricultural sector.

III. **Design and strengthen tailored incentives schemes for smallholder farmers to enable equal access to digital and green innovations**. Smallholders and young farmers face disproportionate barriers to adopting digital technologies due to limited capital to invest, knowledge gaps, and structural disadvantages. To ensure that the digital transitions are socially inclusive and do not widen existing rural inequalities, policymakers should implement incentives schemes specifically tailored to the needs and capacities of small-scale farmers, especially farmers under 10 hectares. This may call for reshaping the current Payments for small farmers (PSF) with targeted funds aiming at investing in digital technologies on small-scale farms. This may include higher co-financing rates for them to invest in digital tools, bundled support packages which combines incentives with tailored advisory support, simplified access procedures, dedicated funding windows and social conditionality bonuses that prioritise small farms employing vulnerable groups, women or young farmers.

IV. **Tailor, strengthen and promote trainings, advisory support, digital capacity building activities for rural innovations and demonstrative plots**. The successful uptake of digital technologies in agriculture depends not only on financial incentives, but also on the availability of accessible, continuous, and practical training and advisory support. Therefore, the trainings need to be systematically integrated with support schemes. The rural development policies need to encourage or require participation in certified training or advisory programmes as part of the eligibility criteria and focus on the upskilling and reskilling of rural workforce, especially for women, young people and older farmers. Additionally, the trainings shall be modular and tailored to the needs and understanding of the farmers to ensure inclusion. Public-private partnerships aiming at trainings, advisory support and digital capacity building shall be encouraged between government bodies, agri-tech providers, institutions and agricultural cooperatives to ensure that the trainings are practical, future-oriented and market relevant. The government should provide Training of Trainers programmes regarding the use of digital technologies local, government-led advisory service providers, and institutions, who are in close contact with farmers on field level. Furthermore, the involvement of civil servants in the training of trainers programmes regarding the use of digital tools and technologies can provide direct and trusted support to farmers on local level. Lastly, demonstrative plots can provide farmers with hands-on experience on the use and benefits of digital technologies with practical trainings and advice, that can increase the uptake of digital technologies on their own farms.

V. **Establish robust data governance frameworks to protect farmers' rights and ensure fair and transparent use of agricultural data**. As digital technologies become embedded in agricultural practices, ensuring responsible and transparent data governance is essential for protecting farmers rights, increasing trust and unlocking the full value of data generated on a farm level. The lack of clear rules on data ownership, access, sharing and usage, poses risks for farmers to lose control over their own operation information and risk becoming dependent on dominant agri-tech platforms. A comprehensive agricultural data governance framework may include the recognition of farmers as the primary data owners, mandatory transparency and fairness clauses in digital service contracts, standardised data-sharing protocols and interoperability rules ensuring that farmers can move their data between systems to avoid vendor lock-ins. Furthermore, the national data governance frameworks shall be aligned with EU frameworks such as the Data Act, Digital Markets Act, and Code of Conduct on Agricultural Data Sharing by Contractual Agreement.

VI. **Leverage agricultural data to strengthen CAP cross-compliance and quantify the environmental, social and economic impacts of digital agriculture measures**. To increase the effectiveness, transparency and accountability of the CAP, Member States shall strengthen the systematic utilisation of collected agricultural data, including geospatial, sensors-based, administrative and remote sensing data. This could essentially support both compliance monitoring and impact assessment, particularly in relation to environmental, economic and climate objectives. Furthermore, social impacts can be measured by utilising agricultural data. The share of local labour force, share of gender and young people in the labour force, and rate of adoption (such as the use of different digital solutions) can measure the impacts that digitalisation has created or contributed to. Developing harmonised indicators and methodologies to translate the collected digital data into quantifiable metrics on environmental performance (e.g. GHG reduction, biodiversity indicators, soil health improvements) and on economic performance (e.g. comparison of yields, use of inputs) enables a robust measurement of the actual effects of the use of digital tools. Furthermore, facilitating public access to aggregated data enables research and innovation as well.

VII. **Promote open-source platforms and farmer-led data infrastructure to safeguard data sovereignty and prevent agricultural-data monopolies.** The European Union may find it beneficial to support the development and maintenance of open-source digital platforms and farmer-led data infrastructures to ensure that digitalisation in agriculture promotes fair access, transparency and farmer empowerment. By providing targeted support through rural development funding and innovation instruments (such as European Agricultural Fund for Rural Development (EAFRD) and EIP-AGRI), the CAP can help scale community-driven solutions that enable farmers to manage, control, and benefit from their own data. Furthermore, clear data portability requirements shall be incorporated to avoid the risk of vendor lock-ins, and to guarantee that data collected by farmers can be easily transferred across platforms without restrictive barriers.

Building upon the findings of assessment of the environmental, social and economic impacts of digitisation in agriculture, as well as the country-specific case studies that provided contextual insights, the potential effects of the recommendations can be understood through their contribution to the three pillars of sustainability. The recommendations are expected to deliver tangible results when effectively implemented. To demonstrate their multidimensional impact, the table below maps each of the six policy recommendations against the three core pillars of sustainability. This overview illustrates how the recommendations contribute to a more integrated and balanced approach to digitalisation in agriculture, ensuring that technological progress aligns with broader sustainability objectives.

Table 7: The potential effects of recommendations on the pillars of sustainability

Nr.	Recommendation	Potential effects on the pillars of sustainability		
		Environmental	Social	Economic
I.	**Establish and strengthen a dual investment approach targeting rural digital infrastructure.**	The increase in uptake of digital technologies in agriculture can lower GHG emissions.	Ensures fair and equal access to digital tools and network in rural areas. The use of digital tools can make the agricultural sector more appealing for women and young people as well.	Increases efficiency of the agricultural sector by introducing digital tools.
II.	**Combine and promote synergistic investment incentives in digital technologies and renewable energy systems.**	Contributes to reducing the GHG emissions of the agricultural sector via renewable energy generation.		Increases competitiveness and resilience of the agricultural sector.
III.	**Design and strengthen tailored incentives schemes for smallholder farmers and young farmers to enable equal access to digital and green innovations.**	Contributes to reducing GHG emissions of the agricultural sector, and positively influences the biodiversity.	Ensures fair and equal access to agricultural subsidies and grants, ensuring fair opportunities to invest in technology.	Increases competitiveness and resilience of smallholders. Increases food security due to increased productivity, especially in the local context.
IV.	**Tailor, strengthen and promote trainings, advisory support and digital capacity building activities for rural innovations.**	Increases environmental awareness by farmers.	Ensures fair and equal access to knowledge, lowering the digital skill gaps and ensures the reskilling / upskilling of rural workforce.	Increases competitiveness of rural workforce.
V.	**Establish robust data governance frameworks to protect farmers' rights and ensure fair and transparent use of agricultural data.**		Increases trust in digital solutions among farmers and other stakeholders.	Ensures farmers' ownership over their data, and avoids vendor lock-ins.
VI.	**Leverage agricultural data to strengthen CAP cross-compliance and quantify the environmental and economic impacts of digital agriculture measures.**	Contributes to assess the impact of digitalisation on the environment (e.g. GHG emission, soil health).	Clear and transparent communication of the quantified environmental benefits can positively change the perception of agriculture among young people.	Contributes to assess the impact of digitalisation on economic (e.g. yields, input usage etc.).
VII.	**Promote open-source platforms and farmer-led data infrastructure to safeguard data sovereignty and prevent agricultural-data monopolies.**	Enhanced platform access can result in more accurate datasets, thus inspiring more environmentally appropriate decision-making and actions.	Increased trust in digital technology platforms among farmers. Limits data sovereignty- and transparency concerns.	Enhanced levels of digital technology uptake, especially among smaller farms, inspiring an increase in digital investment and productivity. Limits economic risks posed by agri-data monopolies.

Source: KPMG (2025).

Annex I – Chapters and research questions (17) coverage

Table 8: Chapters and research questions coverage

Chapters	Research Questions
Chapter 3.1	RQ10: What are the main characteristics of farmers adopting digital technologies?
	RQ12: What are the key digital technologies currently used in agriculture, and how widespread is their adoption across different EU regions and farm size?
	RQ13: What are the most promising digital solutions for improving sustainability and productivity in agriculture?
Chapter 3.2.1	RQ1: To what extend does digitalisation contribute to reducing greenhouse gas (GHG) emission in agriculture?
Chapter 3.2.2	RQ3: How can precision agriculture and digital technologies optimise farm management and reduce environmental impacts?
Chapter 3.3.1	RQ4: *Are small-scale farmers at disadvantage in adopting digital technologies compared to larger farms?*
	RQ5: *What measures could help ensure fair access to digital farming technologies for small-scale farmers?*
	RQ6: *How can policy interventions prevent a two-speed digital transition in EU agriculture?*
	RQ7: *How does digitalisation in agriculture affect employment patterns, job creation, and job losses in rural areas?*
	RQ11: What skills and training do farmers need to benefit from digitalisation?
Chapter 3.3.1.2	RQ8: *Can digitalisation attract younger generations to farming, and what policies could support this transition?*
Chapter 3.4.1.1	RQ14: What are the investment costs associated with adopting digital farming technologies, and what funding mechanisms are available to support farmers?
Chapter 3.4.1.3	RQ9: What factors drive or hinder the adoption of digital technologies among different types of farmers?
	RQ2: What challenges do farmers face in adopting digital technologies for GHG reduction, and how do these challenges differ by farm size and regions?
Chapter 3.4.2.1	RQ15: What are the risks of corporate consolidation in the agri-tech sector, and how could this impact farmers' access to digital tools?
Chapter 3.4.2.2	RQ15: What are the risks of corporate consolidation in the agri-tech sector, and how could this impact farmers' access to digital tools?
Chapter 3.4.2.3	RQ15: What are the risks of corporate consolidation in the agri-tech sector, and how could this impact farmers' access to digital tools?
Chapter 3.4.2.4	RQ16: How is agricultural data currently governed, and what are the risk associated with data monopolization in precision agriculture?
	RQ17: What safeguards could be introduced to ensure fair competitions and protect famers' rights over their data?

Annex II – Final list of collected and analysed literature

1) A. Bragaglio et al. (2023): A comparison between two specialized dairy cattle farms in the upper Po Valley. Precision agriculture as a strategy to improve sustainability. Clean. Environ. Syst.

2) A. Casson et al. (2022): A multidisciplinary approach to assess environmental and economic impact of conventional and innovative vineyards management systems in Northern Italy. Sci. Total Environ.

3) A. E. Stone (2020): Symposium review: The most important factors affecting adoption of precision dairy monitoring technologies

4) A. Guerrero, A.M. Mouazen (2021): Evaluation of variable rate nitrogen fertilization scenarios in cereal crops from economic, environmental and technical perspective. Soil Tillage Res. 213, 105110.

5) A. L. Duguma, X. Bai (2025): How the internet of things technology improves agricultural efficiency

6) A. Stromberg, P. Howard (2023): Digital Agriculture Industries

7) A.F. Colaço, J.P. Molin (2018): Variable rate fertilization in citrus: a long term study. Precis. Agric. 18, 169–191.

8) AG Open: Precision Farming GPS and Auto-steering Kits

9) Abiri et all. (2023): Application of digital technologies for ensuring agricultural productivity

10) Agricover (2022): 1000 farmers use Crop360 digital farming platform

11) Agritech Digest (2024): After Securing the Biggest AgTech Deal Ever, AGCO Makes Another Big Move in Smart Farming

12) AgTech (2024): How IoT Sensors in Agriculture are Helping Farmers Manage Livestock Operations Efficiently

13) AgTech (2024): Livestock Farming Technology: Benefits, ROI and Automation Solutions

14) AgTech (2024): Top 10 Reasons to Upgrade to Cattlytics for Automated Cattle Management Solution

15) AgTechNavigator (2024): The adoption conundrum. EU plans to tackle insufficient take-up of agricultural digital solutions among small farmers

16) Annosi et al (2020): Digitalization in the agri-food industry: the relationship between technology and sustainable development

17) ARC (2018): Digital Consolidation – Entrenching Agrichemical Companies and Industrial Ag?

18) ARC (2024): Remote Control and Peasant Intelligence

19) Autio, E. (2017): Digitalisation, ecosystems, entrepreneurship and policy.

20) Autoritatea pentru Digitalizarea României (2023): Raport de analiză a practicilor și politicilor relevante în domeniul European

21) Avelino, F., Wittmayer, J. M., Pel, B., Weaver, P., Dumitru, A., Haxeltine, A., . . . O'Riordan, T. (2019): Transformative social innovation and (dis)empowerment. Technological Forecasting and Social Change, 145, 195-206.

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23) aydi Technologies (2025): Labor Shortages in Agriculture: Leveraging Technology for Efficient Workforce Management

24) B. Nowak (2021): Precision agriculture: where do we stand? A review of the adoption of precision agriculture technologies on field crops farms in developed countries. Agricult. Res. 10(4), 515–522.

25) Bahlo et al (2019): The role of interoperable data standards in precision livestock farming in extensive livestock systems: A review

26) Balafoutis et al. (2017): Precision Agriculture Technologies Positively Contributing to GHG Emissions Mitigation, Farm Productivity and Economics.

27) Balafoutis, A.T.; Evert, F.K.V.; Fountas, S. (2020): Smart farming technology trends: Economic and environmental effects, labor impact, and adoption readiness. Agronomy.

28) Barbanova et al (2023): Digital transition: Long-term implications for EU farmers and rural communities

29) Barrett, H.; Rose, D.C. (2020): Perceptions of the fourth agricultural revolution: What's in, what's out, and what consequences are anticipated? Sociol. Rural.

30) Bayne, K., Damesin, S., & Evans, M. (2017): The internet of things – wireless sensor networks and their application to forestry. NZ Journal of Forestry, 61(4), 37-41.

31) Bioland (2025): Representing the future of agriculture

32) Bio-Siegel (2025): The EU organic farming logo and the national German Bio-Siegel

33) Boursianis, A.D.; Papadopoulou, M.S.; Gotsis, A.; Wan, S.; Sarigiannidis, P.; Nikolaidis, S.; Goudos, S.K. (2020): Smart irrigation system for precision agriculture. The AREThOU5A IoT platform. IEEE Sens. J.

34) Bragaglio et al. (2023): A comparison between two specialized dairy cattle farms in the upper Po Valley. Precision agriculture as a strategy to improve sustainability.

35) Bucci et al (2020): Measuring a farm's profitability after adopting precision agriculture technologies: A case study from Italy.

36) Butu et al (2024): Romania's rural digital transformation and implications for agriculture

37) Butu, V. Dragomir (2024): Comparative analysis of precision and digital agriculture adoption in Romania and Western Europe

38) C. Chen, J. Pan, SK Lam (2024): A review of precision fertilization research. Environmental Earth Sciences, 71 (9), pp. 4073-4080.

39) Caixa Bank Research (2022): The use of water in agriculture: making progress in modernising irrigation and efficient water management

40) CEJA (2023): Policy paper: Smart farmers for smart farming

41) Chazarra et al (2020): Adaption of a Traditional Irrigation System of Micro-Plots to Smart Agri Development: A Case Study in Murcia (Spain)

42) Climate ADAPT (2023): Precision agriculture

43) Council of the European Union (2025): From screens to fields: how digitalisation is transforming agriculture. Research paper.

44) CropLife Europe (2021): EU Code of conduct on agricultural data sharing by contractual agreement

45) Dairy News Today (2024): The growth of milk production in Estonia reached a historic high of 895,000 tons in 2023

46) Dandrifosse et at. (2024): Automatic quality control of weather data for timely decision in agriculture

47) Davion et al. (2023): Feed Conversion Ratio (FCR) and Performance Group Estimation Based on Predicted Feed Intake for the Optimisation of Beef Production

48) Demeter (2021): Understanding Farmers' Adoption of Smart Technology

49) Demeter (2025): Demeter Certification

50) Digital Economy and Society Index (2022): Full European Analysis 2022

51) Deutsche Landwirtschafts-Gesellschaft (2023): AI is an issue on almost every second farm in Germany

52) Dorea et al (2019): Drivers for the development of an Animal Health Surveillance Ontology (AHSO)

53) Ducksize: Robot in use: Farmdroid for seeding & weeding. Accessed 12.06.2025.

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Annex III – The interviewed stakeholders for the case studies, by countries

Table 9: The interviewed stakeholder type by countries

Nr.	Member State	Interviewed stakeholder type	Definition of stakeholder type
1	Estonia	Farmers	Representative of an Estonian dairy non-profit association of natural and legal persons.
2		Farmers	Representative from an Estonian farmers' cooperative.
3	Romania	Farmers	Representative from a Romanian's farmers' association.
4		Software provider	Representative from a Romanian private company, offering data processing services.
5	Germany	Farmers	A single person engaged in agriculture, raising living organism for food or raw materials.
6		Software and hardware provider	A single person providing software and hardware solutions, tools, components for agricultural-related activities.
7	Spain	Software and hardware provider	A single person providing software and hardware solutions, tools, components for agricultural-related activities.

Source: KPMG (2025).

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