

# THE ROLE OF DIGITALIZATION IN SUSTAINABLE AGRICULTURE

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**Abstract:** *ICT, digital and smart tools are an integral part of a competitive agriculture in the 21st century. The world's population is growing, which also means that demand for food will increase, so there is a need to increase agricultural productivity (increasing output/input factor efficiency), for which technological innovation is essential. An important aspect is that some factors of production in agriculture are limited (land, water, etc.), so a fundamental issue for farmers in agriculture is how to carry out their agricultural activities in a sustainable and cost-effective way. Innovative and modern solutions are needed to increase productivity in agriculture in a sustainable way. Digitalisation, of which data and the information derived from data are an integral part, is the basis for these innovative solutions. Technological progress and digitalisation are making a major contribution to the emergence of sustainable agriculture.*

*The aim of the present study is to briefly describe the development and milestones of agriculture, based on a literature review, and to highlight the importance of agricultural digitisation, especially from the perspective of sustainable agriculture.*

**Keywords:** *Sustainable agriculture, Digitalisation, Innovation, ICT tools, Smart farm*  
(JEL code: Q1, Q2)

## INTRODUCTION

The three basic questions of economics: what? for whom? how to produce? In the latter case, in the concept of how to produce, the input factors used play a decisive role, which are incorporated into the price of the products produced and processed, and thus represent costs for the farmer (PUPOS et al. 2021). For farmers, as for all other economic units, the important goal is to achieve the economic optimum and increase profitability, and for this purpose the use of ICT (Information Communication Technology), IoT, smart, precision tools and technologies is essential in day-to-day activities. Nowadays, ICT tools have become an integral part of our lives, and are therefore the pillars of modern, state-of-the-art agriculture (THAPA et al. 2020). By using ICT tools, farmers can obtain up-to-date data and information on weather, crop conditions, new and innovative technologies, input prices, and input use (PUPOS et al. 2021).

The concept of precision agriculture, which includes ISO-BUS connectivity and GIS (Geographical Information System) based soil monitoring, crop condition assessment and crop mapping, is inevitable in this field. Industry 4.0 has significantly expanded the concept of precision agriculture, for example, the aforementioned mapping can be done by drones, which provides much more accurate maps with higher resolution (PAN-DA et. al, 2018). The monitoring of crop status: weed control,

identification of diseases, pests and interventions can also be done faster, efficiently and with optimal input use through the use of ICT and IoT (Internet of Things), thus reducing the environmental impact and the use of pesticides (KOUNTIOS et al. 2023).

Digitalization in agriculture is the process of using data-rich software, hardware, and services to increase productivity and efficiency while reducing costs, labor requirements, environmental impact, and agricultural externalities (TANKOSIC et al. 2024; GETAHUN et al. 2024).

In fact, digital solutions will make agriculture more sustainable, more efficient in production and the digitalisation trend in agriculture will have a positive impact on the social, economic and environmental dimension of rural areas (PÉLUCHA et al. 2023). In the European Union, the digitalisation of agriculture is an important and topical issue, through which global agricultural problems such as the safe and adequate feeding of the world, the conscious and optimal use of scarce input resources, and the reduction of environmental pressures can be mitigated (EUROPEAN COMMISSION, 2021).

## MATERIALS AND METHODS

The study primarily used an analytical approach to achieve its research objectives, focusing on the interaction between

digitalization and sustainable agriculture. The methodology of the study is based on a comprehensive analytical review.

During the secondary information gathering we examined the importance of digitisation in agriculture by using international and national scientific publications, textbooks and studies. In our literature search, we used the following sources: Eurostat, FAO, EMIS, World Bank, Google Scholar, Research Gate, Web of Science, Science Direct. We used the following keywords and their combinations in the search:

- Digitalisation of agriculture
- ICT tools in agriculture
- ICT for agriculture, e.g. in the field of digital agriculture
- Sustainable crop production
- Precision farming
- Smart farming
- Green Deal

In addition to the keywords used above, we also considered it important to use only relevant and relatively recent articles and studies. The literature was selected by relevance and year of publication, focusing on the use of current and relevant literature.

## RESULTS AND DISCUSSIONS

### Digital ICT tools in agriculture and the concept of the smart farm

The development of agriculture has taken place and is taking place in different parts of the world with different intensities and at different rates. Table 1 summarizes the major milestones and dates of emergence of digitalization of agriculture (SZŐKE – KOVÁCS, 2020; RAJ et al. 2021). The table includes the first foundational step for each technology, its development where appropriate, but dating the introduction of a technology is not always straightforward, as it is not always clear when a technology moves from scientific discovery to prototype, beta testing and then to the standardised commercial product category (LOWENBERG – DEBOER, 2022).

Looking at the history of agricultural development, agricultural production has increased through the use of new technologies, irrigation, fertilisers and pesticides. In Germany, in the 1920s, a farmer harvested an average of 1.85 tonnes of wheat per hectare; today, wheat yields average 7.6 tonnes per hectare (BALL et al. 2001, RAJ et al, 2021). In America, in the 1930s, one farmer produced enough agricultural produce for four people, 40 years later this ratio had risen to 73 people, and thanks to innovation, technology and engineering, by 2010 a farmer was producing and providing food for 150 people a year and 164 in 2016 (STATISTA, 2022). At the same time, agriculture will have to provide 70% more food for a growing population by 2050 using fewer inputs (water, pesticides, land) (MATTHIEU et al. 2018).

In the 21st century, the use of ICT tools plays a crucial role in all economic sectors, enabling more efficient production and operations. ICT tools enable (agricultural) business managers to make decisions, produce and manage their businesses faster and more efficiently. Up-to-date information

and data are essential for both production and sales, and help to improve efficiency in production, while in sales the lack of information can lead to a competitive disadvantage (CSÓTÓ, 2013). According to Csótó, the concept of ICT includes software (applications, decision-support programs), hardware (smartphones, computers, laptops, tablets, etc.) and the Internet (information source) (CSÓTÓ, 2013; BALINT et al. 2025). Nowadays, digital literacy is an expected competence, although the lack of digital literacy is a problem in the agricultural sector (PÉNTEK et al. 2025).

**Table 1. Milestones in the process of digitalisation of agriculture**

| Year | Technology, development activity  | Company, organisation           | Country               |
|------|---|---------------------------------|-----------------------|
| 1974 | Electronic identification of animals  | Montana State University        | USA                   |
| 1983 | Use of GPS  | USA Yamaha                      | USA Japan             |
| 1987 | Use of drones   | SoilTeq                         | USA                   |
| 1992 | (spraying, fertilizer application)  | Lely                            | Netherlands           |
| 1997 | Computer controlled variable rate application (VRT) of fertilizer           | Beeline<br>Yara                 | Australia<br>Norway   |
| 2006 | Milking robot   | Trimble                         | USA                   |
| 2009 | GNNS (Global Navigation Satellite System) controlled agricultural machinery | Ag Leader                       | USA                   |
| 2011 | N-sensor (nitrogen fertilizer signal(s))                                    | Ecorobotix<br>Naïo Technologies | Switzerland<br>France |
| 2013 | Automated sprayer section control   | Class                           | Germany               |
| 2017 | Row closing   | Harper Adams University         | England               |
| 2022 | Planting robot  | John Deere                      | USA                   |

*Source: own edits (FAO, 2022, based on LOWENBERG-DEBOER, 2022)*






Looking at the history of the development of agriculture, digitalisation is a major milestone in the agricultural sector. Technologies that were previously considered traditional are

being replaced by new, more efficient, innovative, digital technologies, smart solutions. Today's modern and competitive agriculture is inconceivable without the use of digital tools and farm management software, smart solutions. Up-to-date, up-to-date data play an important role in informed and efficient decision-making. Mobile applications and farm management software provide farmers with up-to-date data and information on crop conditions, market prices (input and product prices), weather conditions, which help farmers in their daily and all kinds of decision making. Based on the above, the digitalisation of agriculture creates the opportunity for the farming processes, management to be based on data-driven decision making and to be an integral part of the smart farm. Table 2 shows the components of a data-driven

smart farm. The first most important element is the crop, which is actually the beginning and the end of the farm management cycle, in the initial concept by sowing and planting and in the final concept by harvesting. Monitoring the status of the crop from sowing, planting to harvesting is an integral part of the smart, data-driven farm. Management or treatment zones are homogeneous territorial units within a plot, through which interventions can be tailored to reduce the use of inputs (pesticides, herbicides, etc.), improve yields, reduce environmental stress, and in fact form the basis of precision farming (SAIZ et al. 2020; THAKKAR et al. 2024).

The sub-categories of the platform are sensors and remote sensing, which can be used to collect data on crops, soil or, where appropriate, weather. Platforms can be placed

**Table 2. Components of the data-driven economy**

| Category  | Subcategory         | Category | Subcategory  |
|---|---------------------|----------|--|
|    | <b>Culture</b>      |          | Precision farming and the smart farm<br>Management zones                           |
|   | <b>Platform</b>     |          | Remote sensing (satellite, drones)<br>Ground sensors                               |
|  | <b>Data</b>         |          | Big Data<br>Internet of Things (IoT)<br>Mapping<br>Information systems (GIS, FMIS) |
|  | <b>Decision</b>     |          | Artificial Intelligence (AI)<br>Decision Support Systems (DSS)                     |
|  | <b>Intervention</b> |          | Variable Rate Technology (VRT/VRA)   |

Source: based on own editing (SAIZ et al. 2020)

on agricultural vehicles (tractor, combine, etc.) or fixed to the ground within the plot, such as local weather stations (TRENDOV et al. 2019). Near-ground sensors (proximal sensors) provide signals from the ground to the plot by placing the sensor in contact with the ground or within 2 m of the ground. Remote sensing has been a key element in the development of the smart economy, whereby useful information about the plot (crop, land) has become available via satellites. The satellites providing agricultural information are Landsat in the US, Sentinel in Europe, RapidEye constellation, GeoEye. There are numerous possibilities for farmers

to collect satellite data (KIANI et al. 2022). A new concept and technology in this respect is the use of thermal imaging cameras. One of the most important components of a smart farm is data. The fundamental difference between a conventional farm and a smart farm, apart from the level of mechanisation, is that the latter allows farmers to collect up-to-date information on a given plot of land or crop. One of the tools for presenting the collected data in a consistent form is the map (vegetation index map, weed map, yield map, etc.), which provides the basis for decision-making by farmers. The maps enable farmers to delimit management and

intervention zones. The next step after data consolidation is the interpretation of the data, which informs the decision on how and why to intervene. Data management software helps farmers to make decisions, but also allows them to monitor what is happening on the farm (LAKATOS, 2019; KIANI et al. 2022; SAIZ et al. 2020).

Nowadays, the applications of drones and robots are becoming more and more diverse in all industries, including agriculture. Drones have been used for precision spraying in Japan since the 1980s. Spraying and fertilisation using drones offers many advantages for farmers: no trampling damage, no fuel costs, high area coverage (10-17 ha per hour), optimisation of crop water requirements, pesticide savings of up to 30% (TÓTH, 2021). Drones and sensing technology are an integral part of Agriculture 4.0 and the 5th pillar of agriculture is artificial intelligence and robotisation, while robotisation is also closely linked and interacts with artificial intelligence, information and communication technology and sensor technology. Technological changes in industry also have an impact on the technologies used in agriculture (BÁRTFAI et al. 2018). Digital technologies have an important role to play in the development and operation of an efficient and sustainable agriculture. One of the key components of current technologies is the acquisition of up-to-date data and information using sensor technology and multispectral cameras, and the processing of the data, through which cost reductions and output increases can be realized (ARZA -GARCÍA & BURGESS 2023; BHARDWAJ et al. 2025). Digital technologies are now widely available in all EU Member States, but there is a huge gap in the

way these technologies are used. There are several reasons for this, the first is the capital required for the initial investment, the second is the digital competences and skills needed to use these technologies and in many cases farmers perceive them as complex to use and apply, which discourages them from adopting new and innovative technologies (European Commission, 2019; PATAKI et al. 2021).

### Digitalisation and sustainable agriculture

Mention of the European Green Deal agreement is essential in the context of agricultural sustainability, whose strategic goal is to achieve a modern, sustainable, competitive agriculture. Agricultural stakeholders are involved in the Farm to Fork strategy through the following themes:

- developing a sustainable food chain with a focus on food safety
- biodiversity, preserving plant and animal diversity
- maintaining healthy forests and increasing forest cover
- contributing to the Zero Pollution Action Plan by preserving and conserving natural resources (water, air, soil)

Precision sensing, IoT and drone platforms form the operational backbone of digital agriculture by enabling high-resolution, spatially explicit monitoring and variable-rate interventions. Digitalization—sensors, IoT, AI/ML, remote sensing, blockchain, and digital twins—enables more efficient, monitored, and data-driven farming (MILLER et al. 2025; GETAHUN et al. 2024; DELANEY et al. 2025).

Digital agriculture technologies and their application are linked to the Green Deal through Farm to Fork in several ways, such as positive environmental impacts: opti-

**Table 3. Summary table use of ICT tools, digital tools and sustainability benefits**

| Technology           | Functions   | Sustainability benefits                                | Sources                                |
|----------------------|---|--|--|
| IoT field sensors    | Continuous microclimate/soil monitoring                 | Enables optimized irrigation and inputs                | (GETAHUN et al. 2024)                  |
| UAV remote sensing   | High-res crop health mapping                            | Early stress/disease detection; targeted interventions | (ZHANG, et al. 2019, KHAN et al. 2024) |
| NIR point sensors    | Chemical composition at standoff points                 | Lower-cost spectral monitoring                         | (DELANEY et al. 2025)                  |
| GPS/VRT machinery    | Variable-rate seeding/fertiliser/pesticide application  | Input reductions and yield efficiency                  | (GETAHUN et al. 2024)                  |
| Soilless IoT systems | Controlled-environment monitoring (hydro/aero/vertical) | Year-round high-efficiency production                  | (DUTTA et al. 2025)                    |

Source: own editing based on GETAHUN et al. 2024; ZHANG, et al. 2019; KHAN et al. 2024; DUTTA et al. 2025)

mised chemical application, optimised seeding, irrigation, soil conservation, drone spraying, while digitalisation also contributes to increased productivity. The latter also means that self-cost reductions can be realised, which is a pillar of competitiveness. It also helps in yield estimation, crop harvesting and traceability, which also contribute to safe food production. Thus, based on the above, the digitalisation

of agriculture also contributes to social, environmental and economic sustainability (TAKÁCSNÉ, 2022; TAKÁCSNÉ, 2020; TUREK, 2013).

Climate-smart farming is about putting new, state-of-the-art technologies into practice, based on the pillars of improving farmers' income and living standards, sustainably increasing agricultural productivity, adapting to climate

change and reducing greenhouse gas emissions (TAKÁCSNÉ, 2022).

### The benefits of digitization

#### *Improving productivity and efficiency*

- Digital technologies such as sensors, robotics, and data-driven tools are revolutionizing European agriculture by enabling precise decision-making. This leads to increased productivity and more efficient use of resources.

Time savings and process simplification

- Digital tools help simplify operations and save time for farmers.

#### *Sustainability and resource management*

- Digital technologies promote sustainability and reduce resource consumption. Digital platforms contribute to reducing chemicals and improving traceability, which increases food safety.

#### *Innovation, attracting younger generations*

- Digitalization supports innovative business models and the use of digital, innovative technologies will make agriculture more attractive to the younger generation. ILIOPOULOS et al. 2025)

### Barriers of digitization

#### *Costs*

- High costs of digital solutions, farmers often cite the significant costs associated with digital adoption as a major barrier.

- The disadvantaged positions of small farms

#### *Lack of knowledge and infrastructure deficiencies*

- Lack of digital skills needed to use new digital tech-

nologies

- Limited internet connectivity, particularly in rural areas

#### *Trust issues and data and data privacy concerns*

- Issues related to data ownership and control pose significant barriers (ILIOPOULOS et al. 2025)

The CAP aims to make European agriculture more sustainable while ensuring a fair standard of living for EU farmers. It ensures the competitiveness and sustainability of agriculture through a combination of direct payments, market measures and rural development measures. EIP-AGRI is an acronym for the European Innovation Partnership for Agricultural Productivity and Sustainability, launched in 2012 to deliver the Europe 2020 strategy for smart, sustainable and inclusive growth (European Commission, 2023). Table 4 shows the H2020 projects related to digital agriculture and their brief description (ILIOPOULOS et al. 2025, VORONKOVA et al., 2025).

Horizon 2020 is the EU's biggest research and innovation programme. Through the Framework Programme, more than €200 million has been earmarked for research and innovation (R&I), for the introduction of digital technologies in the agricultural sector. These funds are aimed at the development and deployment of digital technologies that enable precision farming, sustainable agriculture and more efficient food production (European Commission, 2023; HORVÁTH et al. 2017).

The digitalisation of agriculture and sustainability are strategic global, European and national policy objectives. Some examples are the European F2F Strategy, the German Agricultural Field Strategy 2035 and the German Sustainability Strategy. The F2F strategy also emphasises the importance of digitalisation by optimising the use of agricultural inputs, which contributes to reducing environmental

**Table 4. H2020 projects related to Digital Agriculture**

| Title   | Link | Topic   | Link  |
|---------|------|---|---|
| IoF2020 |      | The project aims to accelerate the use of IoT technology in agriculture and food to improve food safety, increase productivity and strengthen European competitiveness.   | <a href="https://www.iof2020.eu/">https://www.iof2020.eu/</a>                               |
| Atlas   |      | The project aims to address the lack of data interoperability (the ability for different systems, devices or software to work together) in agriculture by creating an open platform that provides hardware and software interoperability using sensor data. | <a href="https://www.atlas-h2020.eu/objectives/">https://www.atlas-h2020.eu/objectives/</a> |

| Title Link           | Topic   | Link  |
|----------------------|---|---|
| <b>Demeter</b>       | The project aims to deploy farmer-centric, interoperable smart farming platforms in 18 countries through 20 pilot projects, involving 60 partners, 25 deployment sites and 6000 farmers. It will optimise multi-farm data analytics and provide an open and interoperable data integration model. It also aims to support sustainable farming and food production systems, ensure safe food and create new business opportunities for the farm and the wider agri-food economy.       | <a href="https://h2020-demeter.eu/">https://h2020-demeter.eu/</a>         |
| <b>SmartAgriHubs</b> | The project aims to accelerate the digital transformation of the European agri-food sector by building a network of digital innovation hubs to boost the uptake of digital solutions by the agricultural sector. It includes 28 flagship innovation experiments that will showcase digital innovations in agriculture and improve the maturity of digital innovation services to ensure that digital innovations are rolled out across Europe and widely adopted by European farmers. | <a href="https://www.smartagrihubs.eu/">https://www.smartagrihubs.eu/</a> |
| <b>agROBOfood</b>    | It aims to accelerate the digital transformation of the European agri-food sector through the introduction of robotic technologies. Its main objective is to create a sustainable network of digital innovation hubs that will boost the uptake of robotics solutions by the agri-food sector with the aim of maximising the return on European investment and transforming the sector.   | <a href="https://agrobofood.eu/">https://agrobofood.eu/</a>               |
| <b>Romi</b>          | Its aim is to develop a platform for leaders and innovators in agri-technology robotics in Europe. The network aims to reduce and overcome the barriers that agri-food companies face and to help them access the latest robotic agricultural solutions.  | <a href="https://agrobofood.eu/">https://agrobofood.eu/</a>               |
| <b>Pantheon</b>      | Its aim is to develop a new method for monitoring plant health in order to detect plant diseases and to take corrective action. The main objective is to develop approaches for continuous monitoring of plant health with unprecedented precision.   | <a href="https://pantheonproject.eu/">https://pantheonproject.eu/</a>     |

Source: own editing based on GETAHUN et al. 2024; ZHANG, et al. 2019; KHAN et al. 2024; DUTTA et al. 2025)

pressures, helps farmers to produce more efficiently, and informs consumers about food and how food is produced. In Germany, agri-digitalisation is a national priority and one of the 12 objectives of the 2035 agricultural field strategy (JOSEPH et al. 2022).

Biotechnology could be a future research topic in the study of digitization and sustainable agriculture. Digital agriculture and biotechnology are revolutionizing modern farming by combining cutting-edge technologies with biological innovations to promote sustainable development. Artificial intelligence (AI), the Internet of Things (IoT), and data ana-

lytics will also play an important role in this regard, these tools optimize resource utilization and improve productivity with real-time monitoring (NATH & TRIPURA, 2025).

## CONCLUSION

The digitalisation of agriculture is helping to ensure a sustainable food supply in many ways. Various policies and strategies, such as the F2F strategy, the German Agricultural Field Strategy 2035 and the German Sustainability Strategy, and various research and development projects within the

European Union, H2020, are helping to foster agricultural digitisation.

ICT tools, farm management software, IoT, precision agriculture technologies (agricultural drones, sensors), artificial intelligence contribute to the sustainability of agriculture and optimise farmers' costs, as well as greatly improve production efficiency. Digital technologies can provide consumers with more detailed and transparent information on the conditions of production and nutritional content of food, and farmers with information and better understanding of consumer preferences and trends. This new dynamic between consumers and producers could also be crucial for achieving sustainability goals.

The adoption of digital agriculture and the use of its tools and technologies are hampered by a number of factors, such as high investment costs, lack of expertise, lack of knowledge, lack of trust on the part of farmers, farm structure (small farms), lack of uniform legislation on drone spraying. Developing an appropriate strategy that reflects the above-mentioned problems and includes solutions to these problems could be one of the solutions. Solutions could include financial support for farmers, the provision of advice and training, and the development of uniform drone legislation within the EU.

The European Union can help in several ways to promote the adoption of digital, sustainable agricultural practices. The combination of public subsidies, environmental policies, and public investment in R&D are effective tools for increasing both agricultural productivity and sustainability, which has a significant impact on future policy development.

Based on the literature research, it can be stated that digitalization, new technologies and IoT contribute greatly to the development of sustainable agriculture, but the process of its completion is a multi-stakeholder process, in which not only farmers have to play a role, but also Member States, agricultural policy makers, farmers' organizations and educational institutions.

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