ART —— Analysis and Research Team

RESEARCH PAPER

From screens to fields: how digitalisation is transforming agriculture

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Introduction

When the first GPS-based field monitoring system appeared in 1995, it marked the dawn of a new era for farming[1]. This innovation led to the rise of precision agriculture, a data-driven approach that helps farmers cut costs, stay competitive and reduce environmental impact. Initially, GPS technology was used on only 0.8% of U.S. cropland. Fast forward twenty years, and self-guided systems were being used on 60-70% of North American cropland, on 30-50% in Europe, and on over 90% in Australia[2]. By then, 70-80% of new farm equipment sold in the EU incorporated precision agriculture technologies[3], highlighting the rapid growth and widespread adoption within two decades.

Today, **smart farming solutions** are practically **ubiquitous**, and the benefits are undeniable. Precision sprayers with in-built cameras and image-recognition software can reduce herbicide use by 70-90%[4]. Soil moisture and temperature sensors promise to save up to 50% of the water used in irrigation[5]. Scouting weeds, plant diseases and pests is just a smartphone-app away[6]. Cutting-edge technologies sprout by the minute, with most recently generative artificial intelligence (gen AI) breaking new ground on the fields[7]. At the same time, this transformative process is not without shortcomings: along data-related and security concerns, **gaps continue to exist** in technology access, infrastructure and education.

Moreover, parallel to the proliferation of innovative digital solutions, challenges in the global context of agriculture have also multiplied. Farmers in the EU are contending with a **complex web of interrelated issues**, including climate change, ecosystem degradation, increasing competition, market disruptions and rising production costs, exacerbated by crises such as Covid-19 and the war in Ukraine. These pressures periodically reach critical levels, as witnessed in 2024.

Amid a period of **heightened political attention** to the agricultural sector, this paper looks at digitalisation as a trend that can play an important role in shaping the future of farming. While there is **no single bulletproof solution** to the many challenges farmers face, the paper shows that **digitalisation** – when implemented thoughtfully[8]– **can be**

part of the answer. The starting point is that digitalisation is an undeniable reality, which has already reshaped agriculture to a certain extent. Nonetheless, to fully harness the potential of new farming technologies, their benefits must be weighed alongside the risks and limitations, including social impacts. Digitalisation alone will not solve the underlying structural problems of the sector and the global challenges it faces. Yet, by gradually transforming farming practices with a holistic approach, these advancements can be an opportunity and act as a catalyst to tackle broader agricultural issues.

Although digitalisation impacts every aspect of the agrifood chain, potentially improving traceability and transparency of products along the whole supply chain, this paper concentrates mainly on the farming phase.

The first part of this paper introduces the concept of **digital 'revolution' in agriculture**, offering a snapshot of the current state of a slow-burning process and the EU's place within. The second part scans the key drivers of digitalisation and looks at the potential benefits of digital solutions. It is organised around three primary and deeply **interlinked challenges: efficiency, environmental sustainability and socio-economic resilience**. The third part focuses on the risks of the process and the issues to address to maximise the benefits. By identifying possible pitfalls, this part aims at **encouraging further policy reflexion** on how to mitigate them, thereby **enhancing broader uptake** and better use of digital technologies.

A revolution in the making?

'How can agriculture, one of the oldest human activities, reinvent itself in the digital age?' [9]

Agriculture dates to around 12,000 years ago: its birth revolutionised the way people lived and led to the emergence of the earliest civilizations. Since this very first, so-called 'Neolithic Revolution', agriculture has come a long way. Following various subsequent pivotal moments[10], the sector has been seeing a major overhaul under the digital transformation. The **integration and application of cutting-edge technologies** (detailed in the annex) - coming originally from outside into the farm production system - are heralded as the key to a more efficient, responsible and sustainable agricultural sector. An overwhelming part of the literature refers to the current phase as '**Agriculture 4.0**' or the '4th agricultural revolution', to describe the **paradigm shift** from a 'traditional' to a primarily digital modus operandi throughout the entire agricultural value chain.

However, against the narrative calling this transformation a 'revolution', there is increasing criticism and nuancing in the literature. Experts warn against **excessive techno-optimism** and highlight the **uneven adoption and benefit-distribution**[11].

Digitalisation in agriculture is a slow burning process: innovations such as precision agriculture, genetically modified crops and robotics have been developing for decades. After a longer period of non-linear, incremental change, the last few years saw a real surge of new technology, especially AI. Recognising this potential, the Draghi Report[12] identifies agriculture as one of ten strategic EU sectors where accelerated AI development could significantly enhance business models. Yet, while there are many examples of digital transformation benefits, uncertainties remain. Factors like the rate of innovation and adoption, geographical differences, regulatory environments and market dynamics all affect the success of this transformation[13].

State of play

Since GPS was adapted from military use to farming three decades ago, paving the way for innovations like drones, sensors and data analytics, digital technologies have steadily transformed agriculture. The process is extensive and growing, offering new opportunities for data-driven decision-making and smart farm management. The expansion curve is impressive: in 2023, the global digital farming market was valued at $24.91 billion, and is projected to reach $71.48 billion by 2030, with a 16.3% compound annual growth rate[14]. Nonetheless, digital agriculture faces adoption challenges[15]. Compared to other sectors, digital adoption in agriculture has been slower, due to infrastructure limitations, high investment costs, a skills gap and the complexity of agriculture (variability in climate, soil, crops and practices).

The EU within the global agricultural technology (AgTech) landscape

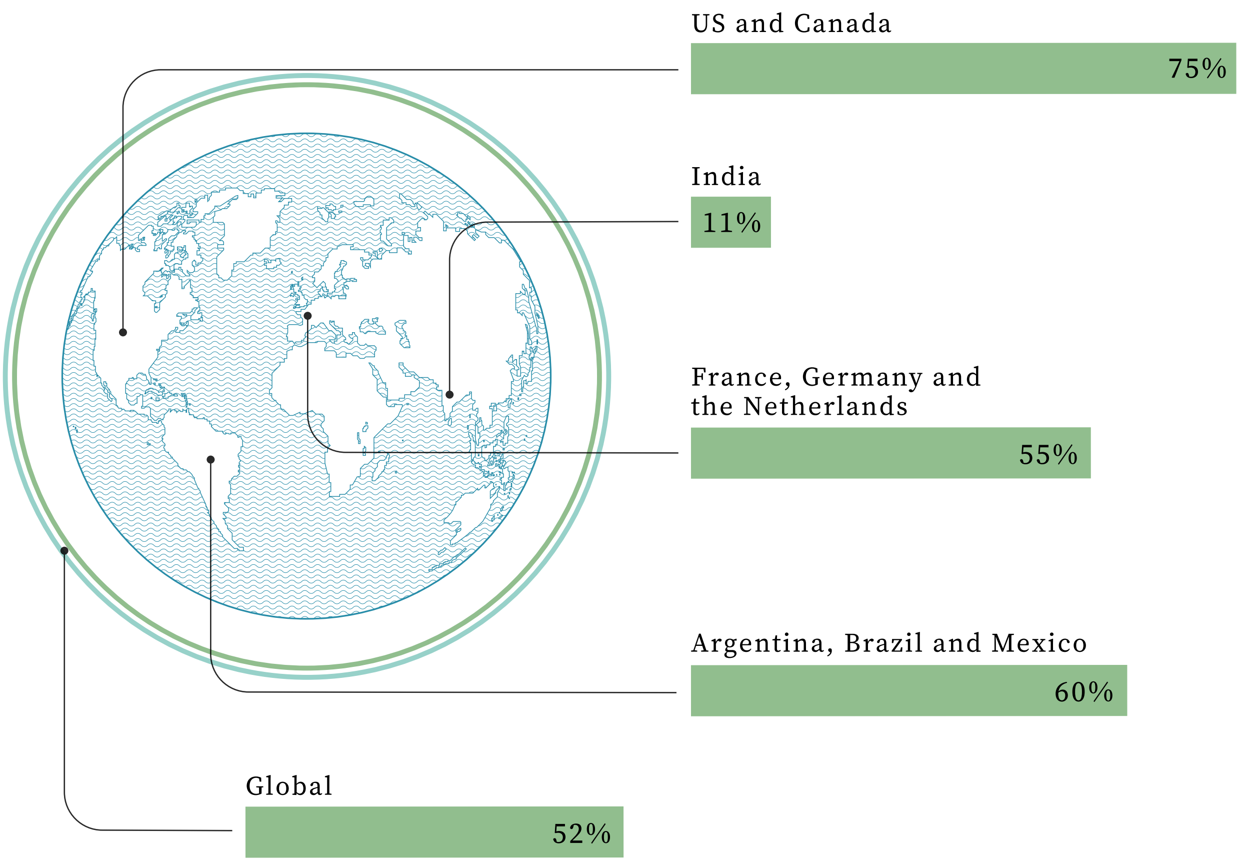
The **global AgTech landscape is highly dynamic**, with different regions leading in various technologies. The US, China and in the EU several Member States are advancing in AI, Internet of Things and data analytics to boost productivity and sustainability.

The EU is making notable strides, particularly in **sustainability-focused** AgBioTech (insect-based feed, new crop breeds), farm management solutions, novel farming (urban, indoor, vertical) and agriculture marketplaces[16]. Several EU countries stand out in AgTech innovation. The **Netherlands**, known as the 'Silicon Valley of Agriculture'[17], leads in resource-efficient farming, with over 290 AgTech startups[18] and a focus on greenhouse technology and vertical farming[19].

Germany excels in sustainability and precision farming, home to major AgTech providers like Bayer CropScience and BASF Digital Farming. It leads in precision equipment and biotechnology research. Northern Italy merges its traditional machinery production with innovative technologies. The Po Valley's unique ecosystem creates an ideal environment for implementing these advancements, positioning the region as a case study for enhancing agricultural production through digital solutions[20]. Meanwhile, Central-Eastern Europe, especially **Poland, Czechia and Hungary**, are also quickly advancing in adoption with strong academic and government support.

AgTech adoption worldwide in 2024

Currently using or willing to adopt at least one technology, % of respondents.



Source: Global Farmer Insights 2024, McKinsey & Company, October 2024.

Targeted policies and funding are crucial for driving agricultural innovation in the EU. Both policymakers[21] and the industry[22] are pushing to accelerate digital technology and smart farming adoption. The Common Agricultural Policy (CAP) supports sustainable farming and innovation[23], while Horizon 2020 has allocated over €200 million for agricultural research and development (R&D)[24]. The **Strategic Dialogue on the Future of EU Agriculture**[25] advocates measures to support digitalisation in a responsible manner. The EU also benefits from a strong **network of research institutions**[26], collaborating with the private sector to advance smart agriculture[27]. These efforts can foster a homegrown AgTech ecosystem and reduce reliance on external technologies, such as those from the US.

The **US** has been a leader in AgTech, focusing on **large-scale technological integration and efficiency**. Major companies (such as John Deere, Trimble, or Agco) drive advancements in machinery, drones, sensors, automation, AI and data analytics. The US is a leader in biotechnology, genetically modified organisms (GMOs) and crop genetics[28], supported by an **innovative ecosystem of tech hubs**, research institutes, government policies[29] and venture capital[30].

In **Asia-Pacific**, efforts focus on **boosting productivity to meet the food demands** of growing populations. With its vast agrifood sector, **China** has become a major AgTech player[31], advancing precision agriculture, smart irrigation, robotics and genetic engineering, supported by government policies and funding[32]. **India** promotes digital agriculture with initiatives like the 'Per Drop More Crop'[33] scheme to improve irrigation. **Japan** excels in agricultural robotics, AI, internet of things (IoT) and crop genetics.

Israel, a pioneer in desert agriculture and water management, is leading in innovations like drip irrigation and biological pest control[34].

Key drivers and benefits: a global context

To ensure a more equitable and sustainable future, farmers face the challenge of improving yields, making informed management decisions and reducing waste. Digital farming tools offer a promising solution to these challenges35. The core drivers of digitalisation in agriculture - efficiency, environmental sustainability and socio-economic resilience - are deeply interconnected. As a result, the benefits of many digital technologies are holistic, addressing these crucial aspects simultaneously.

Efficiency

The increasing demand for food driven by global population growth underscores the urgency of accelerating the digital transformation of agriculture. To meet the needs of a projected global population of around 10 billion by 2050, significant improvements in productivity are essential, primarily through intensifying the use of existing farmland rather than expanding into new areas[36]. This highlights the crucial role of digital technologies in enhancing productivity[37], while balancing food security with the preservation of natural resources. The central challenge lies in **producing more with fewer resources** – including less land, water and labour – amidst growing uncertainties[38].

The efficiency driver translates into diverse aspects in various regions of the world. In many parts of Africa, Asia and Latin America, the priority is significant production growth to prevent food insecurity, while in the EU, a major agricultural producer and exporter[39], the focus is on **managing risks** such as weather unpredictability, market volatility and crop diseases. Digital farming risk management solutions like pest and weed scouts, soil monitors and real-time sensors help EU farmers reduce risks, **optimise resource use** and protect yields. Although the EU does not face immediate food security issues, global food insecurity could have an indirect impact, through trade disruptions, geopolitical instability and possible increased migration from the affected regions. Such secondary challenges make digital agriculture advancements essential both domestically and abroad.

Environmental sustainability

Ensuring global food security must go hand in hand with environmental sustainability. As the Organization for Economic Co-operation and Development (OECD) notes, a key challenge for the agriculture sector is to feed an increasing global population, while at the same time reducing the environmental impact and preserving natural resources for future generations[40]. **Agriculture significantly affects the environment**, accounting for 11% of the EU's domestic greenhouse gas emissions, biodiversity loss, soil degradation, water extraction, chemical and nutrient pollution. The drive for increased global productivity risks worsening these impacts, but **agriculture can also help the environment** in various ways, including by trapping greenhouse gases in crops and soil or reducing flood risks through specific farming practices[41]. For example, technologies such as agricultural intelligence platforms using drone and satellite imagery can identify flood-prone areas for preventive action, while farm management software can help optimise operations by tracking inputs, monitoring soil health, and enhancing carbon sequestration.

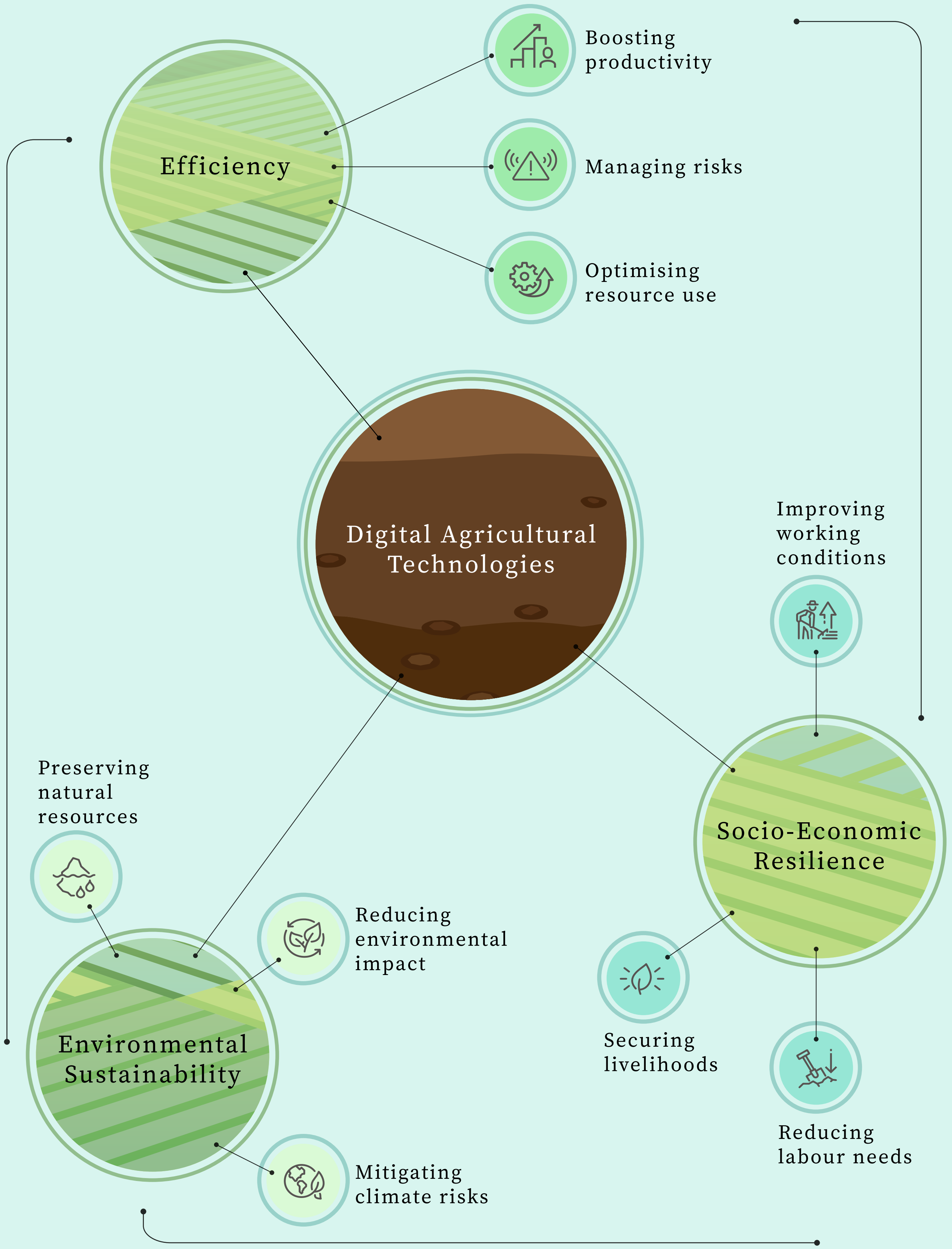
Climate change, in turn, greatly affects agriculture, with **weather extremes** increasingly **disrupting crop yields and livestock productivity** in the EU[42]. While climate risks cannot be entirely eliminated, digital farming solutions can help mitigate them[43]. For instance, variable rate technologies – tools that adjust inputs like water or fertilizer based on specific field conditions – reduce resource waste and improve crop resilience to climate variability, while real-time field monitoring systems help manage risks and optimise farming practices.

Socio-economic resilience

Rising input costs, volatile markets, climate risks, heavy regulation, and global competition make **farming increasingly difficult, driving many to abandon it**. Farmers' income remains well below the average wage[44], and 22% of rural populations are at risk of poverty[45]. The number of EU farms has dropped by 37% from 2005 to 2020, with small, family farms, essential to rural communities, struggling the most[46]. Despite various initiatives and policy objectives[47], small-scale farms face disadvantages compared to large ones, with less capital for technology, limited access to credit, and greater risk aversion. The disappearing small farms are being replaced by larger farms, **threatening biodiversity-rich landscapes and worsening rural decline**[48]. Moreover, farming faces a **generational crisis**[49], with only 5.6% of farms run by those under 35, while over 31% are run by farmers over 65[50], many of whom lack digital skills.

Key socio-economic factors, like profitability, quality of life, rural viability and generational renewal, are central to whether digital tools succeed. Digital technologies, such as precision farming and farm management software, can enhance efficiency, reduce costs, and make farming more predictable, offering farmers **a more secure livelihood**. These tools can also improve working conditions, reduce physical and mental strain, and make farming more attractive to younger generations, helping to **address the ageing workforce**. Digitalisation can also significantly **reduce the need for labour** in agriculture by automating tasks such as planting, harvesting and monitoring crops through the use of advanced machinery and precision agriculture technologies. However, challenges like high investment costs, uncertain returns, lack of digital skills and data mistrust remain barriers to adoption. The success of digitalisation in agriculture will largely depend on overcoming these obstacles and ensuring farmers and rural communities can fully benefit from technological advancements[51].

Key drivers and benefits



An example from the fields: resource optimisation with digital solutions

'How can critical concerns such as water and fertiliser use be optimised in crop farming?'

Water and nitrogen are essential for crop production and food security. Farmers have used irrigation and fertilizers for centuries to boost productivity, with modern agriculture now being the largest consumer of water, accounting for 40% of total water use in Europe[52] and 70% of freshwater withdrawal globally[53]. However, this reliance on water has made agriculture both a major contributor to and victim of water scarcity[54], a problem likely to worsen due to climate change[55].

Similarly, nitrogen fertilizers are key to increasing crop yields[56], but their efficient use is challenging. Uniform fertilizer application can lead to overuse[57], which harms the environment by degrading freshwater, acidifying soil and raising greenhouse gas emissions[58]. The production of synthetic nitrogen fertilizers is energy-intensive, with additional geopolitical concerns over Russia's role as the leading exporter of nitrogen fertilizers and a major supplier of natural gas and potash, both essential for fertiliser production. While agriculture will continue to rely on water and fertilizers, improving their efficiency and sustainability is crucial to protect both water quantity and quality.

Success rates of digital solutions in resource use optimisation (both from an environmental and an economic point of view) vary greatly (fertiliser saving between 1-82%, water saving between 2,5-75%, yield increase between 1-70%[59]), depending on several factors, including crop and soil type, technology type, but both experiments and real-world applications underpin the benefits of digital technologies.

Some concrete examples[60]

- Variable rate drip irrigation used in a 4.5 hectares vineyard in Northern Italy allowed a **17% water saving** compared to standard farm management[61].
- Variable rate irrigation applied in cotton fields in Greece showed a **5 to 34 % savings in water** consumption (Hydrolife project)[62].
- A model decision support system developed for precision irrigation management in outdoor orange and greenhouse tomato crops in Southern Spain revealed a **reduction in irrigation water use by 20%**[63].
- A comparative study of novel irrigation methods revealed the effectiveness of using automatic rain sensors, soil water sensors and evapotranspiration controllers over traditional automatic timer treatments, achieving **water savings up to 75 %**[64].
- A real-time soil nutrient monitoring system combined with a data analytics platform developed by an Estonian startup resulted in **15% of total fertiliser reduction** on a 4,000 hectares cereals and oilseed farm in Estonia, which **saved €56,000 in fertiliser costs** for the farmer and reduced the potential for nutrient runoff and environmental pollution, without compromising yield[65].
- A farmer-assistant robot for nitrogen fertilizing management of greenhouse crops in a greenhouse for cucumber achieved an **18 % decrease in nitrogen fertiliser consumption**[66].
- An experiment with aerial imagery and on-ground detection demonstrated an up to **80% reduction in fertiliser dosage** for vineyard crops, when using site-specific spraying based on the created maps, compared to conventional applications[67].
- The 'GaiaInFarm' project under HORIZON 2020, using monitoring and mapping systems and farm management information system, reported a **50% to 70% decrease in fertilisers usage**[68].

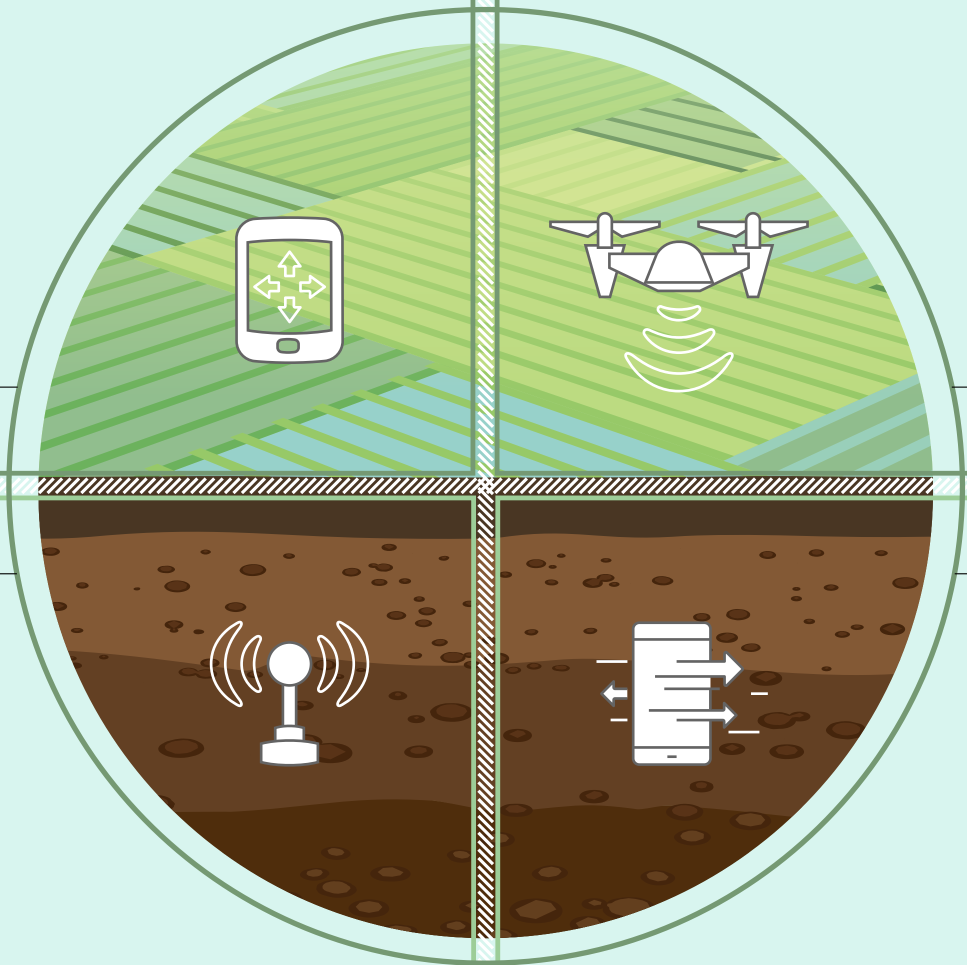
Key technologies for efficient resource management in agriculture

Variable rate technologies

- Adapt to soil heterogeneity
- Increase efficiency by targeting crop needs
- Automate input application based on data
- High potential of reducing greenhouse gas emissions

Drones

- Equipped with sensors for detailed and quick crop analysis
- Help reduce environmental impact by applying spot treatments
- Can reach terrains otherwise difficult to travel
- Save time and costs



Soil monitors

- Provide real-time data on soil moisture and nutrient levels
- Enhance irrigation and fertilisation scheduling
- Reduce input waste
- Improve crop health

Farm Management Information Software

- Synchronise data from various digital farming components
- Facilitate automated data processing
- Calculate the most cost-efficient amount of inputs
- Predict best application windows

Challenges and limitations of digitalisation in agriculture

As smart technologies and farm data continue to grow, **farming is becoming increasingly data-driven**[69]. Digital farming services rely on the data farmers collect and share. This data is compared with other farmers' datasets and those of Agricultural Technology Providers (ATPs) to offer advice on seeding, planting, harvesting, fertilisation and irrigation to maximise efficiency[70]. Data is most valuable when aggregated from as many farms as possible: the more diverse and extensive the data, the more precise and useful the recommendations[71]. Data from nearby farms is especially relevant, as local conditions like microclimate, soil, water resources, pests and farming practices are often interconnected, improving the accuracy of the advice. Best results thus rely on scaling digitalisation, including through partnerships between AgTech and BigTech companies for cloud-based data management[72] to make sure datasets are interoperable and can be combined to draw broader and more accurate insights.

However, the very enabler of progress – data – is also the major source of challenges that can potentially hinder advancement. The '**digital paradox**'[73] of agriculture, where technologies designed to simplify processes can instead become burdensome, emerges on various levels, including infrastructural, social, regulatory and cyber-security limitations. It is therefore important to identify and overcome these limitations in order to maximise the benefits both for individual farmers and society as a whole.

A. Access limitations

The first requirement for benefiting from digital tools is reliable access. Smart machines and digital services depend on a **strong digital infrastructure**, but many rural areas in Europe still lack high-speed broadband[74], despite efforts[75]. **Universal broadband is essential** for these technologies to function effectively and accurately.

A lack of electronic devices, such as smartphones, also limits farmers' access to digital services. This can hinder their ability to meet digital compliance measures, such as the use of geo-tagged smartphone images for area-based subsidies[76]. As a result, the benefits of digitalisation may be undermined, adding challenges for farmers. Additionally, high initial costs, maintenance expenses and a shortage of skilled workers are also major barriers to adopting digital agriculture, as highlighted in relevant studies[77]. Somewhat counterintuitively, the long lifespan of large farming equipment can deter investment, as rapid technological advancements may render even state-of-the-art machines outdated long before their expected lifespan ends. Retrofitting older machinery with new digital components – increasingly available from major farm equipment manufacturers[78]– offers a cost-effective solution, allowing farmers to benefit from the latest technologies without the financial burden of purchasing entirely new machines. However, the pace of **technological obsolescence** still pressures farmers to invest regularly in these upgrades to maintain competitiveness and efficiency.

B. Socio-cultural aspects

A second set of limitations, closely tied to access, involves socio-cultural and behavioural factors, such as **farmers' age, education, openness to innovation** and willingness to adapt. To benefit from smart agriculture and stay competitive, farmers can no longer rely solely on their agronomic knowledge: they need new digital skills. Age and education impact digital literacy[79], and the lack of training in digital platforms is a key barrier[80]. This discourages farmers from investing in costly new technologies, and without the necessary skills, the efficiency of these tools can suffer[81].

Farmers' hesitation to adopt digital solutions often stems from **risk aversion**, rooted in their experience and the uncertainties of farming. The **unclear return on investment**[82] adds another layer of uncertainty[83]. This can particularly affect small-scale farmers, who often struggle to adopt digital technologies that are otherwise cost-effective for larger farms[84]. **Fear of dependency on technology**, loss of control and attachment to traditional methods also contribute to resistance[85]. **Lack of trust** in digital technologies[86], particularly regarding data collection and use, is also a major obstacle, reducing the availability of crucial agricultural data for policymaking, innovation and service development[87]. Compounding this issue is the **fragmentation of agricultural data**, which is often siloed due to **non-interoperable systems**[88]. This limits the potential of digital technologies while benefiting large agribusinesses that form exclusive data-sharing alliances. The trend of traditional agricultural conglomerates increasingly focusing on data acquisition[89] could lead to **further market concentration, weakening farmers' bargaining power**[90] and reducing their share of the benefits[91].

A major challenge in regulating[96] agricultural data[97] is that most of it is non-personal, machine-generated[98], and thus falls outside the scope of General Data Protection Regulation (GDPR). This data is often created on private farms under contracts with Agricultural Technology Providers (ATPs), who collect the data and provide recommendations[99]. Without specific regulations ensuring fair terms, farmers may be at a disadvantage, with the data generated on their farm locked-in by ATPs[100]. This can include **a lack of data portability rights**, meaning the ability to transmit historical data to other service providers if they switch providers or equipment. Such historical agricultural data is crucial for farmers, allowing long-term comparisons to create models and services tailored to their specific needs and conditions. Another issue is the **right to repair**, meaning the right to access the data and software needed for repairs. Without this, farmers are obliged to rely on expensive, licensed repair services that are often hard to find in remote areas. In the debate, while some advocate for '**data ownership**' rights for farmers[101], others[102] suggest this may not be the best solution.

C. Regulatory implications– data related issues

Farmers' **distrust of digital technologies and data sharing** partly stems from the l**ack of clear legal rules** on the consequences of doing so[92], a challenge that has been generating a lot of debate and a multitude of studies on the subject. While the EU has initiated efforts to build a European data economy[93], no specific regulations address smart farming data, leaving ambiguities[94]. Key concerns include the control of and access to data generated on farms (data ownership issue), data lock-in, portability, licenses, privacy, cybersecurity and the fair distribution of digital benefits[95].

D. Cyber-security concerns

A less discussed[103] but critical challenge of digitalisation in agriculture is the sector's vulnerability to cybersecurity risks, for which it is largely unprepared. Farming is particularly at risk due to its **crucial role in global food security** and its lack of historical experience with cyber threats[104]. As the agri-food sector becomes more and more dependent on digital tools, cybersecurity is becoming a growing social concern[105]. In other words, 'there are two types of smart agriculture systems – those that have been hacked and those that will be'[106]. Cyberattacks could include remotely taking over autonomous tractors in order to destroy crops, stealing land valuation data for business manipulation purposes or disrupting the agri-food supply chain of a country[107]. Such acts of sabotage can also be part of a hybrid thread amidst rising geopolitical tensions[108].

Research[109] shows that farmers are vulnerable when it comes to cyber security practices. Additionally, there is a lack of cybersecurity frameworks specifically designed for agricultural technologies. **Raising farmers' digital awareness** and providing cybersecurity education is essential to prevent attacks at the farm level. Moreover, AgTech companies' reliance on cloud infrastructure also means that sensitive information is stored and processed externally, which can lead to potential cybersecurity risks. As the sector becomes increasingly data-driven, establishing tailored standards and clear protocols is vital to help farmers and businesses implement effective security measures[110].

Existing data governance framework[111]

Agricultural data collection and management in the EU has a long history, predating even the Common Agricultural Policy (CAP)[112]. Unlike the more laissez-faire approach to digital transformation seen in other regions, the EU aims to implement well-defined standards for the digital economy, building inter alia on its extensive experience in agricultural data management[113]. Most recently, the Commission's **Strategic Dialogue on the Future of EU Agriculture** emphasised the importance of creating a transparent data governance model, with clear rules on data ownership, interoperability and ethical use to ensure fair and secure data practices for everyone's benefit[114]. Currently, the following are some key elements and initiatives of data governance relevant to agriculture[115]:

- **Data Governance Legislation**: recent horizontal legislative measures, in particular the **Data Governance Act**[116] and the **Data Act**[117] – both central to the European data strategy –[118], are highly relevant to agriculture as they also cover non-personal data. These two complementary legal acts aim to facilitate reliable and secure data access across sectors, while encouraging industrial and technological development. Nonetheless, their horizontal scope limits the applicability to the digital agricultural sector and would need possible sectoral regulations to follow up[119].

- **Common Agricultural Data Space**: within the broader framework of Common European Data Spaces, which promotes the free flow of data for the benefit of European businesses and citizens[120], the **common agricultural data space** specifically targets the agrifood sector. Also referred to as AgriDataSpace[121], its aim is to develop a secure and trusted data space to allow the farming sector to share and access data, improving economic and environmental performance in the field[122]. The objective could however be affected by the same data-sharing trust issues farmers have towards agricultural technology providers, directed towards the regulator: a fear that disclosing on-farm data could help regulators introduce additional or stricter rules[123].

- **Code of Conduct on agricultural data sharing by contractual agreement**[124]: this voluntary, industry-led initiative aims to foster trust in data sharing, by encouraging transparency about data use. It is seen as one of the most comprehensive and holistic attempts for the adoption of a non-binding set of guidelines addressing data sharing in the context of digital agriculture[125]. However, there are limited insights regarding its practical implementation and its effectiveness in enhancing data-sharing processes for farmers and agribusinesses[126].

Digital technologies have not only increased the volume, sources and types of agricultural data but also diversified the actors involved, with the private sector playing an increasing role. This new digital agricultural ecosystem is complex, and so is its data governance. As the field evolves, **new legal challenges are likely to emerge**[127].

Conclusion

The twin transition of digitalisation and sustainability will play a key role in shaping the future of EU agriculture. Digital technologies have immense potential to advance environmentally and socially **sustainable farming practices**, while improving the efficient management of critical resources such as water and nutrients. They can also simplify many aspects of the farming profession, by **improving decision-making** and automating processes, thus potentially offering a better work-life balance for farmers.

While digitalisation is just one aspect of the future of farming and not a comprehensive solution to all the challenges the sector faces, it can positively impact other critical areas for agriculture too, such as risk management, generational renewal, or regulatory and reporting requirements[128]. Combined with other initiatives, it could help create a more resilient and sustainable agricultural landscape.

However, the increasing reliance on data in farming – often referred to as the datafication of agriculture – presents both **benefits and risks**. Many farmers encounter connectivity issues, lack the necessary infrastructure or digital literacy, and are unable to invest in expensive technologies. Rather than bridging the gap, this situation may exacerbate the digital divide. Furthermore, the absence of a clear legal framework governing data sharing, coupled with interoperability challenges and rising cyber threats, undermines trust in digital solutions. It is crucial to address these issues proactively to avoid the risk of digitalisation deepening farmers' discontent, as they may feel sidelined by technologies that impose additional burdens rather than alleviating their challenges.

The success of digital agriculture will depend on how effectively this paradox is addressed. Balancing the opportunities with the challenges will be key to scaling digitalisation in a way that maximises its benefits. This requires coordinated efforts from all actors, starting with strategic, multi-stakeholder discussions[129] to chart the course for the digital transition of agriculture. These discussions could focus on identifying the objectives, the necessary investments, the expected added value and the key enablers of digitalisation. The Commission’s **Digital Transition Toolkit for Policymakers**[130] could provide valuable support and guidance in initiating such conversations. However, given the complexities of agriculture, including vast regional differences and the inherent uncertainties in farming, digitalisation strategies should be **tailored to local context**. Regular impact assessment and data collection on uptake and results are also vital to steer future policy decisions[131].

Ultimately, the digital transformation of agriculture also hinges on farmers’ willingness to adopt digital practices. To encourage this, it is essential that digital tools complement, rather than replace, traditional agronomic knowledge, enhance, rather that diminish farmers' expertise. In addition to adequate advisory and **training support**, clear **data governance frameworks** and **a human-centred approach** to digitalisation[132] can also help building farmers’ trust.

The EU already has initiatives in place that support the **adoption of digital technologies in agriculture in third countries**[133]. In addition to promoting collaboration and knowledge sharing to enhance local productivity, these efforts can help address related challenges such as trade disruptions, increased migration and geopolitical instability that also impact the EU. Further advancement of these initiatives could enhance the EU's role in international agricultural and food security efforts.

Annex - Key technologies and trends

TECHNOLOGY	KEY FUNCTIONS	WHY IT IS USEFUL
Internet of Things and smart sensors	• Real-time tracking of produce and livestock • Monitoring environmental conditions (e.g. soil moisture)	• Optimises supply chain logistics • Enables data-driven decision for efficient resource use • Supports sustainable irrigation practices
Artificial Intelligence	• Turns raw data into actionable insights • Predicts weather patterns and crop health, including anomaly detection	• Improves water and fertilizer management • Detects pests, weeds and animal behaviour issues faster
Drones	• Crop monitoring and field analysis • Seeding and spraying	• Reduces pesticide/ fertilizer use • Enhances crop health and field management through 3D mapping
Robotics	• Harvesting, weeding, seeding, planting, fertilising, picking and packing • Livestock applications like robotic milking	• Increases productivity with 24/7 operations • Reduces labour costs and minimises waste
Autonomous tractors	• Fully automated harvesting and monitoring conditions • Navigation through challenging terrain	• Enhances precision and crop uniformity • Operates continuously, reducing labour costs
Data analytics	• Yield prediction • Field and equipment monitoring	• Helps decision-making on crop selection, irrigation methods and fertilisation practices • Optimises pesticide application, avoiding overuse

TECHNOLOGY	KEY FUNCTIONS	WHY IT IS USEFUL
Precision Farming	• Field variability management • Labour and equipment management	• Maximises yields and minimises waste by targeting resources accurately • Optimises workflows
Regenerative Agriculture	• Monitors carbon sequestration, water quality and biodiversity	• Enhances soil health and water retention • Reduces emissions and soil erosion
Soilless agriculture	• Hydroponics, aquaponics, aeroponics	• Saves land and water, helps avoid soil erosion • Minimises pesticide use
Biotechnology	• Genome editing for pest resistance and higher yields	• Reduces soil toxicity issues and minimises environmental impact
Vertical agriculture	• Year-round crop production in controlled environments	• Maximises space, water and pesticide use • Lower labour and transport costs

References

1 The GPS-based 'Vision System' created detailed, digitalised field maps, and paired the volume of crops harvested with location data. 'Farmers Use Satellites to Boost Efficiency in Cultivating Crops: Agriculture: O.C.'s Rockwell is adapting weapons technology to 'precision farming.' Los Angeles Times, 30 May, 1995. The system was further perfected by farm-equipment manufacturer John Deere, which partnered with Stanford University to develop an autonomous tractor controlled by GPS.

2 Allison Marsch, 'John Deere and the Birth of Precision Agriculture', IEEE Spectrum, 28 February 2018.

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