ICT-AGRI-FOOD

Strategic Research & Innovation Agenda 2025

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1. Executive Summary

The 2025 SRIA renews and broadens the 2019 ICT AGRI-FOOD vision, elaborating and strengthening the concept of “smart farming” as a digitally integrated, climate positive and circular agri-food system that spans production, processing, logistics and consumption. It is explicitly aligned with the European Green Deal (climate neutral EU by 2050), the Farm to Fork Strategy (binding 2030 targets on pesticides 50 % reduction, fertilisers 20 % reduction, antimicrobial sales 50 % reduction) and the reformed CAP 2023-27 (eco schemes and carbon farming pilots).

Where we stand in 2025

Digital uptake has accelerated significantly since 2019, with farm technology adoption more than doubling in many categories. Today, 25% of EU farms use at least one precision technology element such as GNSS auto-steering, drones, or IoT sensors—up from just 15% in 2019. Public and private R&I investment has more than doubled to €950 million annually, spawning transformative projects such as IoF2020, SmartAgriHubs, and the AgriFood Data Space pilot.

Infrastructure improvements are notable: rural VHCN broadband now covers 59% of households, nearly 2.3 times the 2019 baseline of 26%, while rural 5G coverage has expanded to 35% (DESI, 2024). However, significant disparities persist—rural digital infrastructure still lags urban areas, and only 52% of rural adults possess basic digital skills compared to 62% in cities (Eurostat, 2024).

Environmental applications show promise, with 35% of farms now using digital tools for sustainability monitoring, and 24% employing precision pesticide application—both representing substantial increases from 2019 baselines of 18% and 12% respectively (Eurostat, 2024).

* Some of the 2025 figures are projections

Main Systemic Gaps

Fragmented data landscape – Proprietary application silos and lack of interoperability between systems from different vendors impede cross-chain optimization and integration. The European Commission has identified "shortcomings in interoperability" as a significant barrier, as "many digital applications or machines from different brands may not be compatible, making it difficult to share data and integrate data."

Multi-dimensional digital divide – Beyond mere connectivity issues in peripheral regions, the digital divide now encompasses multiple factors. These divides are "influenced by remoteness, turnover of holdings, skills and age of farmers," creating uneven development and adoption patterns across the sector.

Skills and awareness gap – Even where infrastructure exists, adoption lags due to human factors. Many farmers "may not be aware of the potential benefits of digitalisation and may lack the necessary skills and resources to use new technologies," hampering the sector's digital transformation. Also, the potential benefits of digitalization are often not quantified even if the user seek this information

Data sovereignty and trust deficit – Concerns about data ownership, privacy, and control erode confidence in digital solutions. Farmers are increasingly "concerned that their data might be used by third parties without their consent or knowledge," making it "crucial to ensure safeguards for data sharing, data sovereignty, and data security to build trust."

Economic adoption barriers – Financial constraints limit technology uptake, especially for smaller operations. The European Commission notes a "lack of cost-effectiveness" where "the cost of implementing certain digital technologies might be higher than the potential benefits, especially for small-scale farmers."

Climate metrics standardization gap – Lack of standardized carbon, biodiversity, and circularity indicators continues to hamper green finance and policy implementation. Digital innovations could "contribute to more sustainable and resilient agricultural systems" but these benefits "will not emerge on their own" without appropriate frameworks for measurement and accountability.

Governance fragmentation risk – The rapid pace of technological change makes coordinated policy difficult. "Establishing a practical governance framework for this transformation is challenging due to the rapid pace of technological change and the involvement of diverse stakeholders," creating policy incoherence when responding to different priorities.

System resilience integration deficit – Digital tools remain insufficiently integrated into broader resilience strategies. While "digitalization is a critical component for accelerating the implementation of the 2030 Agenda," efforts toward "global resilient agrifood systems enabled by technology" continue to be "hampered by the digital divide" and other structural barriers.

Strategic Priorities

1. **Digital Inclusion and Skills Development** Inclusive digital skills & infrastructure programmes targeting 100% rural 5G and 80% adult basic skills attainment by 2030. The European Commission identifies digital divides influenced by "remoteness, turnover of holdings, skills and age of farmers." Research shows "digitalization can bridge the digital gap, providing farmers in rural areas access to resources and markets," while experts note "building digital literacy" requires urgent attention.

2. **Resilient, Open Technical Infrastructure** Edge-to-cloud automation underpinned by open-source reference stacks and validated in EU Testing & Experimentation Facilities. The European Commission has supported numerous research initiatives like ATLAS and DEMETER, alongside "Testing and Experimentation Facilities (TEF) for AI in Agri-Food." These efforts recognize "digitalization is a critical component for accelerating the implementation of the 2030 Agenda."

3. **Federated Data Ecosystems with Enhanced Sovereignty** Federated, sovereign data spaces that allow farms and SMEs to share insights without ceding raw data. The European Commission is implementing the Data Act which will "facilitate fair data sharing across sectors" by 2025, along with the Common European Agricultural Data Space (CEADS) to "facilitate trustworthy sharing of agricultural data between private stakeholders and public

authorities." The EU Code of Conduct on agricultural data sharing further provides essential guidance on agricultural data usage rights.

4. **Transparent and Participatory Food Systems** Consumer level transparency tools delivering real-time provenance, nutrition and climate impact labels. The ICT-AGRI-FOOD framework aims to "underpin the transition towards more sustainable and resilient agri-food systems with digital technology" and create food chains with greater "transparency." Technologies like blockchain can "improve traceability and transparency of agricultural products in the value chain."

5. **Climate-Smart Agriculture Through Digital MRV** Carbon and biodiversity positive farming incentives backed by low-cost digital Monitoring, Reporting and Verification (MRV) and trustworthy certification. Research demonstrates digital technologies can "increase productivity, reduce footprints and conserve natural resources" while contributing to "more sustainable and resilient agricultural systems." This aligns with the European Commission's Vision for Agriculture and Food emphasizing "social sustainability" and worker protections.

6. **Adaptive Governance Frameworks** Flexible regulatory approaches that evolve with technology and maintain policy coherence. Research highlights challenges in "establishing a practical governance framework for this transformation due to the rapid pace of technological change." The EU vision includes "aligning standards for imported products" while developing "strategies to address policy gaps arising in scenarios of agricultural digitalisation."

7. **Financing and Innovation Support Mechanisms** Targeted financial instruments and innovation support for digital agriculture adoption. The European Commission recognizes "the cost of implementing certain digital technologies might be higher than the potential benefits, especially for small-scale farmers." The EU has committed to "support the entire food value chain through investment and innovation" and to "boost the agri-food sector's competitiveness and attractiveness."

Key Actions

Federated Data Ecosystems with Enhanced Sovereignty

- **Interoperability protocols**: Develop and deploy standardized data exchange protocols that enable farms and SMEs to share insights without ceding control of raw data. This addresses the EU's concern that "data might be used by third parties without consent or knowledge."

- **CEADS implementation**: Accelerate the deployment of the Common European Agricultural Data Space with robust governance frameworks that protect smallholder interests. This aligns with the EU's commitment to "facilitate trustworthy sharing of agricultural data between private stakeholders and public authorities."

- **Decentralized technologies**: Support development of technologies that enable collaborative analytics while preserving data ownership at the source. This supports ICT-AGRI-FOOD's goal to "underpin the transition towards more sustainable and resilient agri-food systems with digital technology."

- **Data Act compliance**: Create agri-food specific implementation guidelines and tools for the EU Data Act. This will help operationalize the Data Act which will "facilitate fair data sharing across sectors" by 2025.

Climate-Smart Agriculture Through Digital MRV

- **Standardized MRV systems**: Establish common frameworks for digital Monitoring, Reporting, and Verification of carbon sequestration and biodiversity enhancement. This supports innovations that help "increase productivity, reduce footprints and conserve natural resources."
- **Distributed ledger certification**: Create certification frameworks based on sensor data and blockchain technologies to ensure transparent verification. This builds on how "specific digital technologies, like blockchain improve traceability and transparency."
- **CAP alignment**: Integrate digital climate metrics with Common Agricultural Policy incentives to ensure policy coherence. This supports the EU vision of "social sustainability" and protecting "the rights of workers."
- **Affordable MRV tools**: Develop simplified, cost-effective monitoring tools accessible to small and medium-sized farms. This addresses economic barriers where "the cost of implementing certain digital technologies might be higher than the potential benefits, especially for small-scale farmers."

Resilient, Open Technical Infrastructure

- **Open reference architectures**: Develop open-source reference implementations for farm-to-fork digital systems. This complements research and innovation projects like ATLAS and DEMETER that "shape digitalisation in EU agriculture."
- **Experimentation facilities**: Expand EU Testing & Experimentation Facilities to validate solutions under diverse farming conditions. This builds on existing "Testing and Experimentation Facilities (TEF) for AI in Agri-Food" in the EU's strategic approach.
- **Modular technologies**: Create modular technology stacks that allow incremental adoption to reduce financial barriers. This supports "digitalization as a critical component for accelerating the implementation of the 2030 Agenda."
- **Resilient infrastructure**: Ensure digital infrastructure can withstand climate disruptions and cybersecurity threats. This supports the ICT-AGRI-FOOD goal of "more sustainable and resilient agri-food systems."

Digital Inclusion and Skills Development

- **Rural connectivity**: Accelerate targeted 5G/6G deployment and satellite internet for remote regions. This addresses digital divides influenced by "remoteness, turnover of holdings, skills and age of farmers."
- **Agricultural digital literacy**: Implement comprehensive literacy programs specifically designed for agricultural contexts. This addresses challenges where "building digital literacy" is identified as needing "to be urgently addressed."

- **Peer knowledge networks**: Develop farmer-to-farmer knowledge exchange to leverage existing expertise in technology adoption. This supports how "digitalization can bridge the digital gap, providing farmers in rural areas access to resources and markets."
- **Accessible tools**: Create multilingual, intuitive digital tools that accommodate diverse user capabilities. This addresses how many farmers "may not be aware of the potential benefits of digitalisation and may lack the necessary skills."

Transparent and Participatory Food Systems

- **Blockchain traceability**: Implement distributed ledger systems providing real-time provenance information. This leverages how "specific digital technologies, like blockchain improve traceability and transparency of agricultural products in the value chain."
- **Standardized impact labelling**: Develop common frameworks for digital nutrition and environmental impact information. This supports the EU vision of "transparency in the food chain."
- **Consumer engagement**: Create platforms connecting urban consumers directly with food producers. This aligns with ICT-AGRI-FOOD's vision where "all stakeholders benefit, but ultimately it is the consumer who will be able to make smarter, healthier and more appropriate choices."
- **Digital marketplaces**: Support community-based platforms that shorten supply chains. This builds on how "stakeholders benefit from greater transparency and streamlined processes along the value chain."

Adaptive Governance Frameworks

- **Regulatory sandboxes**: Develop flexible testing environments for agri-food technology innovation. This supports research showing the need for "strategies to address policy gaps arising in scenarios of agricultural digitalisation."
- **Multi-stakeholder platforms**: Create governance forums for continuous policy adaptation with diverse input. This addresses the challenge of "establishing a practical governance framework for this transformation due to the rapid pace of technological change."
- **Impact assessment tools**: Implement evaluation frameworks for technological interventions across social, economic, and environmental dimensions. This supports the EU's need to "align standards for imported products to guarantee EU's ambitious standards do not lead to a competitive disadvantage."
- **Policy alignment**: Ensure coherence between digital agriculture initiatives and broader EU strategies like the Green Deal and Farm to Fork. This addresses how benefits from digital innovations "will not emerge on their own" without appropriate frameworks.

Financing and Innovation Support Mechanisms

- **Blended finance**: Create hybrid funding instruments specifically for digital agriculture adoption. This addresses challenges where "the cost of implementing certain digital technologies might be higher than the potential benefits, especially for small-scale farmers."
- **Risk-sharing mechanisms**: Implement cooperative approaches to technology implementation for smaller farms. This supports the EU's commitment to "support the

entire food value chain through investment and innovation on farms, cooperatives, agri-food businesses and SMEs."

- **Participatory innovation**: Support farmer-centred design processes that ensure technology meets actual field needs. This aligns with the EU's vision to "boost the agri-food sector's competitiveness and attractiveness."
- **Innovation support**: Establish voucher programs and technical assistance for small farms to access digital solutions. This supports research showing that digitalization can help "reducing the digital divide between urban and rural areas and improve the living standards of agricultural communities."

References

- Bocean, C. G. (2024). A cross-sectional analysis of the relationship between digital technology use and agricultural productivity in EU countries. Agriculture, 14, 519.
- European Commission. (2022). Digital Economy and Society Index (DESI). Brussels.
- European Commission. (2023). Common Agricultural Data Space—Policy Brief. Publications Office of the European Union.
- European Commission. (2023). Digital Innovations for Sustainable and Resilient Agricultural Systems. Brussels.
- European Commission. (2024). Building a European Framework for the Secure and Trusted Data Space for Agriculture. Publications Office of the European Union.
- European Commission. (2024). Strategic Dialogue on the Future of EU Agriculture. Publications Office of the European Union.
- European Commission. (2024). The Digitalisation of the European Agricultural Sector. Publications Office of the European Union.
- European Commission. (2025). Vision for Agriculture and Food. Publications Office of the European Union.
- OECD. (2021). Digital Policies for Better Agricultural Policies. OECD Publishing.
- OECD. (2024). The Evolving Profile of New Entrants in Agriculture and the Role of Digital Technologies. OECD Publishing.

2. Introduction

2.1 Strategic alignment

Four policy cornerstones anchor this agenda, positioning digital technologies not as mere add-ons but as core mechanisms delivering climate, biodiversity, and health goals:

1. **European Green Deal** – Setting the EU's path toward climate neutrality, zero pollution, and restored biodiversity.
2. **Farm to Fork Strategy** – Establishing the food system pillar with concrete 2030 targets: 50% reduction in the use and /or risk of chemical pesticides, 20% less reduction in nutrient losses / fertilizers, 50% fewer antimicrobials, and expanded organic agriculture.
3. **CAP 2023-27** – Reorienting agricultural support through eco-schemes, carbon farming pilots, and digital knowledge transfer networks.
4. **Digital Decade Policy Programme** – Charting digital transformation with targets for universal gigabit connectivity, 5G coverage, digital skills (80% of adults), and cloud/AI adoption (75% of EU firms) by 2030.

2.2 From ICT in agriculture to the digital agrifood ecosystem

While the 2019 SRIA primarily viewed ICT as an enabler of precision farming, today, three significant shifts have expanded both scope and context:

Value chain integration has accelerated as pandemic and geopolitical shocks revealed the intricate connections between farm inputs, logistics, and retail. What began as optional tracking systems have evolved into essential risk management infrastructure.

Convergence of data spaces now bridges previously isolated systems. Cloud-edge platforms and federated learning connect on-farm sensors with enterprise systems, cold chain monitors, and consumer applications, creating continuous digital threads from field to fork.

Climate services integration has transformed sustainability from a reporting exercise to an operational reality. Carbon accounting, biodiversity metrics, and circular material tracking are increasingly embedded in everyday farm management, procurement decisions, and consumer-facing labels.

These shifts are reflected in measurable adoption trends. While precision farming technologies have shown significant growth across Europe, adoption patterns remain uneven. Farm management information systems have reached higher adoption rates among larger operations, while more advanced technologies like blockchain-based traceability solutions show lower penetration despite their potential. Similarly, basic sustainability monitoring tools have seen faster uptake than advanced carbon and biodiversity assessment systems.

As these technologies converge, we see the emergence of a true "digital agrifood ecosystem"—a socio-technical system where data, algorithms, and connected devices create value throughout the supply chain while preserving farmer sovereignty and consumer trust.

2.3 Challenges, Goals, Trends and Adoption Gaps

The systemic gaps identified in Chapter 1 reflect both persistent challenges and emerging barriers. Three intersecting trends have intensified in recent years, driving many of these gaps:

Climate-related disruption has moved from forecast to reality. More frequent and intense weather events—from droughts to floods to heat waves—are affecting yield stability, resource management, and farm risk profiles across Europe. This new climate reality has elevated the importance of digital tools that support adaptation, provide early warnings, and enable access to responsive insurance products.

Data concentration and power asymmetry have emerged as structural concerns. A small group of agri-tech and input suppliers now exert significant control over critical farm and supply chain data, raising questions about competition, access equity, and sovereignty. As data becomes the new currency of agriculture, its governance becomes a matter of strategic importance.

Digital adoption divides persist despite improved connectivity. While mobile tools, precision services, and satellite broadband are expanding their reach, small and medium-sized farms still face multiple barriers—financial, technical, and educational—to adopting and benefiting from these technologies, particularly more advanced AI-enhanced systems.

These trends directly feed the systemic gaps outlined in Chapter 1. Climate disruption exacerbates both the metrics standardization gap and resilience integration deficit. Data concentration reinforces the fragmented landscape and sovereignty concerns. Meanwhile, adoption challenges perpetuate the multi-dimensional divide, skills gap, and economic barriers that hold back progress.

2.4 ICT in Policy Making

Digital technologies have transcended their role in farm operations to become central to the entire agricultural policy cycle—from agenda setting to implementation and impact evaluation. Today's information systems transform diverse data streams into insights that enable more responsive governance and evidence-based decision-making.

The policy functions described below directly support the strategic priorities outlined in Chapter 1. Federated data ecosystems and climate-smart agriculture depend on evidence-based policy design and efficient monitoring. Digital inclusion advances through participatory governance approaches. Food system transparency relies on accountability mechanisms. Meanwhile, adaptive governance frameworks and innovative financing are themselves policy innovations enabled by digital transformation.

ICT supports five essential functions within the policy cycle:

Evidence-based policy design begins with transforming heterogeneous data—market prices, satellite imagery, administrative records, even social media sentiment—into actionable intelligence. Modern techniques such as automated data collection, API integration, and natural language processing help policymakers identify emerging issues and model intervention scenarios with unprecedented speed and accuracy.

Cost-efficient monitoring and evaluation have evolved beyond periodic reporting to continuous assessment. Real-time dashboards now track eco-scheme participation, carbon footprint reductions, and nutrient management improvements, enabling timely adjustments and better alignment with strategic goals.

Participatory governance has expanded through digital platforms that connect policymakers with farmers, businesses, researchers, and citizens. These collaborative spaces broaden the knowledge base, increase policy legitimacy, and facilitate cross-border learning, creating more inclusive and responsive agricultural governance.

Delivery of public services has been streamlined through e-government platforms that reduce administrative burdens while providing more personalized support. Digital service delivery makes regulations more accessible, reduces compliance costs, and extends the reach of agricultural support programs.

Transparency and accountability are strengthened through open data portals, public model documentation, and audit-ready digital systems. Citizens gain visibility into decision processes, while policymakers benefit from cross-border benchmarking and transferred innovations, fostering globally aligned responses to shared challenges.

While these benefits are substantial, digital policy tools also present risks requiring careful management: **privacy and data protection** concerns arise with high-resolution farm data; **digital divides** in infrastructure and skills can exclude stakeholders; **algorithmic bias and opacity** may emerge in automated decision systems; and **resistance to change** can slow adoption due to institutional inertia or implementation complexity.

Addressing these challenges requires strong ethical frameworks, robust security measures, inclusive design approaches, and engagement strategies that build trust and capacity across the agri-food ecosystem.

References

- European Commission. (2022). Agriculture and Digital Agriculture. Publications Office of the European Union.
- European Commission. (2022). Digital Economy and Society Index (DESI). Brussels.
- Nikolov, V., Fielke, S., Jakku, E., Taylor, B., & Verbeke, W. (2023). Digital Innovation Ecosystems in Agri-Food: Design Principles and Organisational Framework. SmartAgriHubs White Paper.
- OECD. (2021). Digital Policies for Better Agricultural Policies. OECD Publishing.
- OECD. (2022). The Digitalisation of Agriculture: Literature Review and Emerging Policy Issues. OECD Food, Agriculture and Fisheries Papers, No. 176.

3. Global Challenges for a Sustainable Agrifood System

The global food and agriculture system faces intensifying, interconnected crises spanning environmental degradation, socio-economic inequalities, and health insecurity. The sustainability challenges of today—climate change, biodiversity loss, deforestation, and malnutrition—are no longer isolated phenomena. They are interdependent, deeply embedded in the structure of global food systems. From production to consumption, the way we manage food systems has profound implications for climate stability, public health, poverty, and equitable economic development.

Recognizing these complexities, international organizations have issued urgent calls for transformation. The UK Foresight Report (Government Office for Science, 2011), FAO’s Future of Food and Agriculture (2022), the IPES-Food Reports (2024), and the US Global Food Security Strategy (2021) collectively highlight systemic vulnerabilities and necessary reforms. These include promoting food sovereignty, redesigning agricultural subsidies, strengthening local food networks, and deploying digital tools for sustainable resource management.

3.1 Sustainable Agriculture and the Food System

Sustainable agriculture now transcends operational and yield efficiency. It incorporates the three pillars of sustainability—economic, environmental, and social. Recent frameworks, such as FAO’s Strategic Framework 2022–31, reinforce that sustainable farming involves equity in wealth distribution, consumer awareness, and local empowerment. Achieving this requires not only technical innovation but shifts in governance, value chains, and public consciousness.

While these strategic goals are widely endorsed, some of the 2030 targets—particularly under the Farm to Fork Strategy—require closer scrutiny. For example, the 50% reduction in the use and risk of chemical pesticides is based on harmonized risk indicators, allowing flexibility through substitution with lower-risk substances rather than absolute reductions in volume. Similarly, the 20% reduction in nutrient losses implies enhanced efficiency and targeted application, not necessarily a uniform 20% cut in fertilizer inputs. Nonetheless, questions remain about the feasibility of these targets across all production systems and climatic zones, especially without negatively impacting yields. Achieving these ambitions will require significant technological, agronomic and economic support mechanisms.

The digital divide in European agriculture manifests distinctly across regions, reflecting broader socioeconomic patterns. Northern and Western European countries typically show digital technology adoption rates of 60-70% among agricultural enterprises, while Southern and Eastern regions average 25-40%, according to Bocean's 2024 analysis. Climate and production systems further influence technology relevance—Mediterranean regions prioritize water optimization technologies, while Northern regions focus on automation to address labour shortages. Central and Eastern European countries with numerous smallholders face unique challenges, as their agricultural sectors often consist of dual structures: very large operations with advanced technology access alongside traditional smallholdings with limited digital integration. Recognition of these regional differences is crucial for developing contextualized approaches to digital agricultural transformation that respond to specific territorial needs rather than pursuing one-size-fits-all solutions.

Digital inclusion in agriculture directly supports multiple Sustainable Development Goals beyond SDG2 (Zero Hunger). The equitable distribution of digital benefits contributes to SDG1 (No Poverty) by increasing smallholder incomes; SDG5 (Gender Equality) through tailored digital services that address women farmers' specific constraints; SDG10 (Reduced Inequalities) by narrowing the urban-rural digital gap; and SDG13 (Climate Action) by democratizing access to climate information services. As demonstrated in Bocean's cross-sectional analysis (2024), countries with more inclusive digital agricultural ecosystems show more balanced productivity gains across different farm types, reinforcing the connection between digital inclusion and broader sustainable development objectives.

The sustainability challenges facing global food systems are particularly acute for smallholder farmers, who produce up to 80% of food in Asia and Sub-Saharan Africa yet often lack access to digital technologies that could enhance their resilience and productivity. Structural barriers such as limited connectivity, low digital literacy, high costs of devices and services, and poorly adapted digital tools significantly hinder technology adoption among these producers. As a result, smallholders are frequently excluded from benefits such as climate-smart advisory services, digital finance, early warning systems, and access to carbon or traceability markets—widening existing inequalities in agricultural innovation. (*FAO, 2021; IFAD, 2023; World Bank, 2017*).

A robust vision of sustainability integrates the Sustainable Development Goals (SDGs), linking agriculture to food security, justice, and planetary boundaries. As shown in studies by Poore & Nemecek (2018), Springman et al. (2018), and the Barilla Foundation’s Food Sustainability Index (EIU, 2018), dietary shifts, waste reduction, and ecosystem preservation are pivotal to ensuring future food system resilience.

3.2 The Role of ICT in Supporting Sustainable Agriculture

ICT plays a transformative role in enabling sustainability transitions. Mobile platforms, smart sensors, and AI-driven analytics are revolutionizing field management, climate adaptation, and input efficiency. Digital connectivity also enhances farmers’ access to knowledge, finance, and markets. However, the true value of ICT lies in supporting system-wide awareness, transparency, traceability, and adaptive governance.

Precision and Smart Farming have matured into an integrated paradigm known as Digital Farming or Farming 4.0. This evolution incorporates real-time data integration, high-level automation, and predictive optimization.

While the terms "precision agriculture," "smart farming," and "digital farming" are often used interchangeably, it can be helpful to conceptually distinguish their emphasis and evolution. The table below outlines how these approaches differ in focus, scope, and technological integration, even though in practice, they increasingly overlap.

Table 1: Conceptual Comparison of Smart Farming, Precision Agriculture, and Digital Farming

Feature	Smart Farming	Precision Agriculture	Digital Farming
Definition Focus	Optimizing complex systems using data technologies	Managing field variability for input efficiency	Full integration of tech-enabled decision-making
Scope of Application	All farm operations,	Specific plots or	Whole value chain,

	systems-level	inputs	internal and external
Key Technologies Used	IoT, AI, robotics, big data	GPS, sensors, variable rate tech	All of the left plus cloud platforms, web services
Primary Goals	Optimize quality, reduce impact	Improve input use, raise yield	Synchronize decisions, minimize waste, reduce risk

The adoption of digital farming requires systemic policy support, capacity-building, and rural infrastructure. These technologies must be scaled inclusively, addressing usability, trust, and connectivity barriers.

The transformative potential of ICT in agriculture remains largely unrealized for smallholder farmers, who face multiple barriers to digital adoption. These barriers include prohibitive costs, non-quantified benefits, limited connectivity infrastructure, inadequate digital literacy, and technologies poorly adapted to local contexts. Bridging this gap requires targeted approaches including low-cost and frugal digital innovations; mobile-based advisory services with voice and image interfaces for farmers with limited literacy; collective digital access models such as village knowledge centers; and digital platforms that respect and integrate indigenous knowledge systems. When designed with these considerations, ICT can become a powerful equalizer rather than a divider, enabling smallholders to leapfrog traditional development pathways. Participatory design approaches that engage smallholders as co-creators rather than passive technology recipients are essential to ensure digital solutions address actual rather than perceived needs, fostering ownership and sustainable adoption.

3.3 Climate-Smart and Carbon-Focused Food Systems

Reports by the IPCC (2023) and Grantham Foundation (2018) signal that time is running out to stabilize planetary boundaries. Emissions from livestock, fertilizer dependence, soil erosion, and monoculture fragility all jeopardize long-term food security. Ensuring climate resilience demands agroecological practices, decentralized supply chains, and smart subsidies that promote nature-positive farming.

Digital technologies offer significant potential to help smallholders adapt to climate change and participate in carbon markets, yet paradoxically, those most vulnerable to climate impacts often have the least access to digital climate services. Context-specific digital advisory focusing on locally relevant adaptation strategies can transform smallholders' climate resilience when delivered through accessible channels. Additionally, blockchain-based carbon credit systems, when designed inclusively, can reward smallholders for sustainable practices while ensuring transparent verification. However, without deliberate efforts to make digital climate services accessible, affordable, and appropriate for resource-constrained contexts, these technologies risk reinforcing existing vulnerabilities. Developing inclusive digital climate solutions requires addressing fundamental infrastructure gaps, creating business models that work at small scale, and building digital climate literacy among vulnerable farming communities.

Bioeconomy principles, as championed in the EU Bioeconomy Strategy (2012, 2018), align agricultural sustainability with circularity and innovation. Converting agricultural waste into energy, packaging, and bio-inputs not only reduces environmental pressure but expands economic opportunity for rural communities.

3.4 Resilience to compound shocks: pandemic, conflict, climate extremes

COVID19, fertiliser price shocks linked to the Russia–Ukraine war, and back-to-back weather extremes highlight hazard stacking throughout the chain. Digital tools cushioned some shocks—robotic milking alerts rerouted technicians when borders closed; AI logistics engines diverted shipments around Black Sea blockades—but weak connectivity or data sharing still caused bottlenecks. The CAP's new risk management toolbox now subsidises on farm drought observatories, while the Cyber Resilience Act mandates security updates for connected machinery. Fertiliser sensor pilots show that real time nutrient mapping can cut application rates up to ~10 % during price spikes.

The digital divide becomes particularly consequential during compound shocks, when access to timely information and services can determine resilience. While most farmers in Europe may technically have internet access—often through smartphones, this basic connectivity does not equate to meaningful digital integration into production, logistics, or decision-making workflows. In practice, the gap lies not only in having a device, but in the quality, reliability, and professional usability of digital tools and services. Farmers who are truly "digitally connected" operate within systems where data flows seamlessly between equipment, platforms, and markets. By contrast, those with only minimal digital interaction remain disconnected from key benefits such as automated risk alerts, remote advisory services, and dynamic input management—especially in crisis scenarios.

3.5 Nutrition, diets and health driven innovation

WHO Europe reports rising childhood obesity; ultra processed foods are a key driver. Plant rich diets could halve food system GHGs, yet demand signals remain weak. Digital levers—from personalised nutrition apps linking grocery loyalty data to diet scores, to AI driven recipe reformulation—are emerging. Supermarkets overlaying Nutri Score with traffic light ecolabels have already nudged shoppers toward lower carbon proteins; suppliers upstream adapt via real time feedback loops to farmers, influencing planting and input choices.

The digital nutrition divide mirrors broader technological inequalities, with smallholder farming communities often having limited access to nutrition-sensitive digital innovations. Yet these communities frequently face the highest burdens of malnutrition, creating an urgent need for inclusive digital nutrition approaches. Mobile-based nutritional advisory services can provide contextually relevant guidance on diverse crop production for improved dietary diversity, while digital marketplace platforms can connect smallholders with nutrition-conscious consumers willing to pay premiums for biodiverse, nutrient-rich foods. To bridge the nutrition-digital divide, technologies must be designed with consideration for offline accessibility, local dietary preferences, and cultural food practices. Participatory nutrition technology development ensures solutions address community-identified needs rather than imposed priorities. As ecolabels and digital nutrition scores become more prevalent, ensuring smallholders can participate in these digital certification systems becomes essential to prevent further marginalization while promoting nutritional improvements.

As digital innovations reshape nutrition and dietary patterns, effective governance frameworks become increasingly vital to ensure these technologies serve all stakeholders equitably.

3.6 Digital Governance and Inclusion

The acceleration of digital agriculture presents both opportunities and risks for equitable food system transformation. Without appropriate governance frameworks, digitalization may concentrate power among those controlling data and algorithms rather than empowering diverse agricultural stakeholders. Digital agricultural governance must therefore prioritize inclusive access, data rights, and algorithmic transparency. For smallholders, data sovereignty—the ability to control and benefit from farm-generated data—is particularly crucial. Collective data governance models such as data cooperatives offer promising approaches to strengthen smallholders' position in increasingly data-driven value chains.

Policy measures to foster digital inclusion in agriculture include universal service obligations for rural connectivity, digital subsidies for resource-limited farmers, and procurement policies favouring inclusive technologies. Additionally, open-source approaches, digital public goods, and interoperability standards can prevent vendor lock-in and reduce adoption costs. The EU's approach to digital agricultural governance can serve as a global model by demonstrating how robust regulatory frameworks like the Data Act and AI Act can be adapted to agricultural contexts while promoting innovation that benefits farms of all scales.

Digital skills development remains fundamental to inclusive transformation. Beyond basic digital literacy, farmers need data literacy to interpret analytics, cybersecurity awareness to protect their information, and business skills to leverage digital market opportunities. Tiered learning approaches that match skills development to farmers' progressive technology adoption journey can help bridge the digital divide sustainably rather than overwhelming novice users.

To effectively track progress in bridging the agricultural digital divide, measurable benchmarks are essential. Key indicators should include connectivity metrics (percentage of rural agricultural areas with reliable broadband/mobile coverage); adoption rates of digital technologies disaggregated by farm size, gender, and age; digital literacy levels among farming communities; and inclusivity of digital agricultural services (measured through accessibility features and language support). According to Bocean's cross-sectional analysis, EU member states with higher digital technology adoption show 3-5 times greater agricultural productivity related to total labour force input compared to those with lower adoption rates. This underscores the urgency of monitoring not just technology deployment but actual usage patterns across diverse agricultural communities to ensure equitable digital transformation.

Implementing inclusive digital agriculture requires targeted investment approaches. Public-private partnerships have proven particularly effective, with public funding addressing basic infrastructure and skills gaps while private innovation focuses on user-friendly applications. The EU's Digital Innovation Hubs specializing in agriculture demonstrate this hybrid approach, providing testing facilities, skills training, and innovation support specifically designed for smaller agricultural enterprises. Evidence from cluster analysis of EU member states suggests a "leapfrogging" potential for regions with currently low digital adoption—strategic investments in agricultural technology can yield disproportionately large productivity gains in these areas when solutions are appropriately matched to local farming contexts and needs.

Ultimately, successful digital governance must balance innovation with inclusion, ensuring technological advancement serves the needs of all agricultural stakeholders rather than only the most resourced. Without this balance, digital agriculture risks reinforcing rather than resolving food system inequities.

References

- Alexander, P., Brown, C., Arneth, A., Finnigan, J., Moran, D., & Rounsevell, M. D. A. (2017). Losses, inefficiencies and waste in the global food system. Agricultural Systems, 153, 190-200.
- Bocean, C. G. (2024). A cross-sectional analysis of the relationship between digital technology use and agricultural productivity in EU countries. Agriculture, 14, 519.
- Economist Intelligence Unit. (2018). Food Sustainability Index. Barilla Center for Food & Nutrition Foundation.
- European Commission. (2012). Innovating for sustainable growth: A bioeconomy for Europe. COM(2012) 60 final.
- European Commission. (2018). A sustainable bioeconomy for Europe: Strengthening the connection between economy, society and the environment. COM(2018) 673 final.
- FAO (2021). Digital Agriculture: Report from the 2021 International Symposium. Food and Agriculture Organization of the United Nations, Rome.
- FAO. (2022). The future of food and agriculture—Drivers and triggers for transformation. Food and Agriculture Organization of the United Nations.
- Government Office for Science. (2011). The future of food and farming: Challenges and choices for global sustainability. UK Foresight Report.
- Grantham Foundation. (2018). The race of our lives revisited. GMO White Paper.
- IFAD (2023). Digitalization for Smallholder Farmers: A Pathway to Inclusive Rural Transformation. International Fund for Agricultural Development, Rome.
- IPCC. (2023). Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.
- Poore, J., & Nemecek, T. (2018). Reducing food's environmental impacts through producers and consumers. Science, 360, 987-992.
- Springmann, M., Clark, M., Mason-D'Croz, D., Wiebe, K., Bodirsky, B. L., Lassaletta, L., & Willett, W. (2018). Options for keeping the food system within environmental limits. Nature, 562, 519-525.
- United States Government. (2021). U.S. Government Global Food Security Strategy (2022-2026).
- World Bank. (2017). ICT in agriculture: Connecting smallholders to knowledge, networks, and institutions (Updated Edition). World Bank Group.

4. Technological State of the Art and Emerging Trends in ICT for Agriculture and Food

4.1 From field to fork: an increasingly integrated digital chain

The seamless operation of food supply chains has become mission-critical in an increasingly interconnected and volatile world. Food security extends beyond sheer availability; it encompasses consistent access to sufficient, safe, and nutritious food that supports active and healthy lives. This includes not only the physical supply of food but also its safety, traceability, and the resilience of the systems that deliver it.

Supply Chain Management (SCM) spans the entire journey of a food product—from raw materials to the consumer's plate. It ensures availability, optimises flow, maintains quality, and ultimately supports consumer trust. As the climate, political, and epidemiological disruptions intensify, resilient SCM is foundational to achieving food security. The strategic integration of digital technologies is transforming traditional agro-food supply chains into responsive, transparent, and adaptable systems.

Digitalisation enables real-time tracking, predictive analytics, and automated control across the food system. IoT sensors measure temperature, humidity, and shock exposure throughout cold chains, reducing spoilage and enabling rapid response to bottlenecks. Blockchain platforms enhance trust by anchoring provenance, handling logs, and transaction histories in tamper-evident ledgers—accelerating recall processes and boosting compliance confidence.

Smart logistics platforms incorporate AI algorithms for dynamic route planning, anticipating delays, and optimising energy use. This digital backbone turns traditionally opaque chains into responsive, cyber-physical systems where each node—from farm gate to retail shelf—communicates condition and demand signals upstream and downstream.

From a resilience perspective, these tools provide early warning and adaptive capacity. Embedded diagnostics and digital twins model scenario responses to stressors like border closures, cyberattacks, or harvest failure. By enhancing visibility, enabling fine-grained control, and supporting rapid reconfiguration, digital technologies increase the food system's ability to absorb and recover from shocks.

Ultimately, the convergence of IoT, blockchain, and AI in supply chains supports all three pillars of food security: availability (via more efficient production and distribution), access (via lower costs and improved logistics), and utilisation (via enhanced safety and nutritional transparency). Investments in smart supply chains are therefore not merely efficiency upgrades, but resilience and equity strategies aligned with long-term sustainability goals.

Food security, as defined by the FAO, exists when all people, at all times, have physical, social, and economic access to sufficient, safe, and nutritious food that meets their dietary needs and preferences for an active and healthy life. This multidimensional concept includes availability (production and supply), access (affordability and logistics), utilization (nutrition and safety), and stability (resilience to shocks).

Digitalization is also giving rise to what is increasingly termed the 'intelligent supply chain'—a system characterized by end-to-end connectivity, autonomous decision support, and traceable events across the logistics network. Enabled by the integration of IoT for real-time condition monitoring and blockchain for secure and tamper-evident traceability, these systems support proactive interventions, improve consumer trust, and accelerate compliance during food safety incidents.

4.2 ICT Infrastructure for Agriculture

4.2.1 Sensing and Data Acquisition

Sensor density and diversity have exploded in agricultural settings. At plot level, low cost LoRaWAN soil probes sample water potential and nitrate every 30 minutes; multispectral UAV missions produce centimetre resolution NDVI maps; Sentinel-2 provides high-resolution optical imagery with a global revisit time of approximately five days, while Sentinel-1 delivers radar data with a typical revisit interval of 6 to 12 days depending on the region and acquisition mode. Combined, they enable frequent and complementary observations for agricultural monitoring, especially in cloudy or high-latitude regions (ESA Sentinel User Guides, 2022).; collars on dairy cows' stream heartrate and rumination data. Globally, connected IoT devices topped 16.6 billion in 2023 and are projected to reach 18.8 billion by end-2024, with agriculture flagged among the five fastest growing verticals.

Hardware costs continue to decrease as adoption volumes rise. A multispectral drone package that five years ago cost €10,000–30,000 can now be obtained for around €5,000, as seen in models like the DJI Mavic 3 Multispectral (DJI, 2023). Stitching and analysis software, such as Pix4Dfields, is typically priced at around €3,500 for a perpetual license, with software-as-a-service options available through annual subscriptions. This reflects a substantial reduction in total entry costs, though professional-grade systems still require significant investment. Soil CO_2 flux chambers are available at < €600 (DIY estimate); DIY field robots leverage opensource ROS stacks and swappable battery packs.

4.2.2 Connectivity Solutions

Rural connectivity keeps pace with technological advancements. 5G Stand Alone rollouts and Low Earth Orbit (LEO) satellite backhaul extend broadband to remote agricultural areas; satellite IoT subscriptions alone are forecast to grow 19% CAGR to a2026.

The increasing penetration of high-capacity networks into rural areas is eliminating one of the most persistent barriers to digital agriculture. Network slicing capabilities in 5G enable dedicated bandwidth for critical agricultural applications, while edge computing reduces dependency on constant connectivity.

4.2.3 Edge Computing and Processing

Edge processors now run convolutional neural nets onboard tractors and drones, performing weed seedling identification in milliseconds without requiring cloud connectivity. This on-device intelligence enables real-time decision making even in remote areas with intermittent connectivity.

The Cyber Resilience Act (CRA) will soon make firmware security and over-the-air update channels mandatory for every connected device placed on the EU market—closing a loophole that left thousands of cheap sensors unpatched and vulnerable to exploitation.

Advanced edge AI processors optimized for agricultural applications are entering the market, with power requirements low enough to enable solar-powered deployment in field conditions. These devices increasingly support sophisticated computer vision, time-series analysis, and autonomous decision-making without requiring constant cloud connectivity.

4.3 Agricultural Data Systems

4.3.1 Data Integration and Management

Data integration platforms specifically designed for agricultural applications are evolving to handle the heterogeneous data sources common in farming operations. These systems aggregate information from sensors, machinery, satellite imagery, weather services, and business systems into unified data lakes that support comprehensive analytics.

Federated learning pilots let algorithms train on distributed farm data without exporting raw telemetry—respecting sovereignty rules while preventing model bias. This approach addresses both privacy concerns and the challenge of building robust models across diverse agricultural conditions.

API standardization efforts are making headway, with initiatives like AgGateway ADAPT and ISOBUS enabling more seamless data exchange between previously siloed systems. This interoperability is crucial for realizing the full value of agricultural data across the value chain.

4.3.2 AI and Advanced Analytics

Agricultural analytics have advanced beyond simple descriptive statistics to sophisticated predictive and prescriptive capabilities. Weather-aware digital twins of crop fields adjust nitrogen prescriptions daily based on integrating multiple data streams. Large language models (LLMs) now summarize sensor anomalies for agronomists in natural language, making complex data interpretable without specialized training.

Computer vision systems grade produce at high speeds and can detect defects as small as 0.2mm that are invisible to the human eye. Hyperspectral imaging can identify contaminants like aflatoxin in grain before silo contamination spreads.

Machine learning algorithms increasingly incorporate domain-specific agricultural knowledge, reducing the data requirements for training effective models. Transfer learning approaches allow models developed for one crop or region to be efficiently adapted to others, accelerating deployment of AI solutions across diverse agricultural contexts.

4.3.3 Simulation and Digital Modelling

Digital Twins in agriculture have matured into sophisticated virtual replicas of farms, fields, or systems that are continuously updated with real-world data. These integrated models combine physical data (e.g., soil moisture, crop stage, weather) with process models and AI to simulate and predict outcomes under various scenarios.

The coupling of Digital Twins with Reinforcement Learning (RL) represents a significant advancement in agricultural decision systems. RL algorithms learn optimal decision policies through interactions with simulated environments, allowing systems to dynamically adapt strategies under changing conditions such as evolving weather patterns or market signals (Goldenits et al., 2024).

What is Reinforcement Learning?

Reinforcement Learning is a machine learning approach where an algorithm learns to make sequential decisions by interacting with an environment. Unlike supervised learning, RL algorithms create their own training data through trial-and-error, observing outcomes from different actions. In agricultural contexts, these actions might include irrigation scheduling, fertilizer application timing, or robotic navigation paths, while outcomes could be yields, resource efficiency metrics, or task completion rates.

Current Applications

RL applications in agriculture currently focus on two main areas:

1. **Robotic Decision-Making**: RL algorithms optimize path planning for UAVs gathering crop health information or monitoring pest traps, helping maximize information collection within battery life constraints. Similar approaches guide autonomous ground robots for targeted spraying and harvesting operations, particularly in fruit production.

2. **Crop Management**: RL shows promise as a decision-support tool for optimizing fertilizer application and irrigation scheduling. Most research focuses on nitrogen management and irrigation timing to maximize yields while minimizing resource use. In greenhouse environments, RL systems help control lighting, stabilize power usage, optimize sensor placement, and determine ideal measurement timing.

The convergence of simulation and learning technologies is particularly promising for complex management tasks where real-time adaptation to changing conditions can significantly improve both efficiency and sustainability outcomes. By training first in simulated environments, these systems can deploy with greater reliability in real-world agricultural settings.

Research Challenges

Despite promising advances, practical RL implementation faces several challenges. Most current applications remain in the research stage, with limited field deployment. The need for numerous training iterations typically confines RL to computer simulations rather than real-world experimentation, raising questions about transferability to actual farm conditions.

Another challenge involves defining clear action sets and reward functions for agricultural contexts. While robotic applications often have well-defined success metrics, crop management involves complex trade-offs between yield, profit, environmental impact, and risk considerations that resist simple optimization (Khanna et al., 2024).

Additionally, farmer acceptance of experimentation remains an open question, as RL's exploration phase requires trying various actions—some potentially suboptimal—to discover effective strategies.

4.4 ICT Applications in Agriculture

4.4.1 Farm Management Information Systems

Farm Management Information Systems (FMIS) have evolved into comprehensive digital platforms that integrate data from multiple sources to support the full spectrum of farm operations. Contemporary FMIS platforms incorporate sensor data, remote sensing, economic models, and predictive weather analytics to create integrated decision environments.

Increasingly, these systems support participatory co-design approaches, where farmers and advisors iteratively contribute knowledge and feedback to tailor digital tools to local realities. This collaborative development enhances adoption, usability, and ultimately the sustainability outcomes of these systems.

Decision support systems (DSS) embedded in modern FMIS allow users to evaluate trade-offs between competing objectives, such as yield maximization, environmental impact, and economic returns. By integrating diverse models and feedback loops, these systems provide actionable recommendations and scenario exploration capabilities.

4.4.2 Precision Agriculture Applications

Precision agriculture has evolved from simple variable rate technology to AI-guided site-specific management systems that optimize production while reducing environmental impacts. The core concept involves data-driven, precise treatments at sub-field or even plant-specific scales, contrasting with conventional uniform application approaches.

Evolution and Current Applications

The development of precision agriculture has followed distinctive phases. Early applications focused primarily on Variable Rate Technology (VRT) and site-specific management. GPS guidance systems became increasingly important after 2011, with many now standard in modern farming operations. Since 2017, Remote-Sensing, advanced Sensors, and UAVs have gained prominence, while AI, Machine Learning, and Deep Learning applications have dominated research since 2022 (Júnior et al., 2024). Most recent innovations increasingly focus on IoT integration, Digital Twins, and real-time analysis systems.

Market adoption varies significantly across technologies. GPS guidance systems have achieved mainstream adoption (Lowenberg-DeBoer and Erickson, 2019), while other promising technologies remain in early adoption phases despite market readiness. These include:

- Camera and AI-guided precise tractor-mounted smart spraying systems
- Autonomous ground-based robots for various field operations
- UAV-based systems for autonomous and precise spraying
- UAV-based seeding of cover crops, allowing planting in standing crops before harvest

These technologies deliver multiple benefits beyond cost reduction, including improved precision, environmental advantages through reduced chemical use, and operational flexibility by enabling operations during previously impractical periods.

Key Application Areas

Precision agriculture technologies contribute to several critical agricultural challenges:

Pesticide Reduction: AI-driven precision spraying systems integrate field sensors, UAVs, and weather data to localize pest detection and trigger spot applications only where needed. Smart sprayers and autonomous robotics paired with AI-based decision support significantly reduce chemical use while maintaining crop protection efficacy.

Soil Quality Management: Digital technologies enhance soil monitoring, mapping, and management through a layered sensing architecture. Remote sensing via satellites and UAVs enables large-scale detection of spatial variability in soil parameters, while proximal sensors deliver field-level resolution of key indicators. When combined with RTK GNSS geolocation, these inputs enable site-specific management strategies that improve input efficiency and reduce environmental impacts.

Robotics and Automation: Precision action implementation has reached maturity in several domains. Laser weeders can now cover large areas at very high resolution (e.g. Andersen et al., 2022); selective spray booms modulate droplets pixel by pixel, cutting herbicide use up to 60%. In livestock, AI-assisted feeders calibrate rations to methane exhalation curves, delivering mitigation certificates alongside milk solids. On the processing line, collaborative co-bots pick soft fruit at 500 pieces h^{-1} with bruise rates below manual benchmarks.

Research Challenges and Future Directions

Despite significant progress, several challenges remain for precision agriculture:

Multi-scale data integration: Merging different datasets from various sensors operating at different spatial and temporal scales presents significant technical challenges. Future research must develop frameworks for effectively combining satellite, drone, ground sensor, and machine data (Storm et al., 2024).

Hybrid modelling approaches: Combining process-based models with data-driven machine learning models offers promising potential but requires further research to create effective hybrid systems.

Advanced detection capabilities: Further advances in multiclass crop/weed detection are needed to improve precision weeding and targeted treatment technologies.

Precision conservation: Extending precision management beyond production to conservation aspects, particularly in response to climate change impacts, represents an emerging frontier (Basso, 2021).

On-farm experimentation: Developing efficient methods for conducting and analyzing on-farm experiments to optimize practices under specific local conditions remains challenging.

Life-cycle assessment: Comprehensive evaluation of the environmental impacts and costs of precision agriculture technologies throughout their life cycles will be crucial for assessing true sustainability benefits.

Unintended consequences: Research must address potential unintended effects of precision technologies, such as cases where variable rate technology leads to increased rather than decreased input use due to farmer decision-making patterns (Basso and Antle, 2020).

4.4.3 Supply Chain Informatics

Blockchain or EPCIS 2.0 event streams slash recall times from days to minutes, as demonstrated in high-value chains such as Parmigiano Reggiano and single-origin cocoa. AI-optimized route planning, informed by real-time border delay APIs, trims 3-5% fuel and spoilage across multimodal cold chains.

Supply chain visibility platforms now integrate data from multiple stages of the value chain, providing comprehensive monitoring of product conditions, chain of custody, and environmental impacts. These systems support both operational efficiency and regulatory compliance, while enabling consumers to access transparent information about product origins and handling.

4.5 ICT Governance and Standards

4.5.1 European Digital Initiatives

The European landscape for agricultural ICT is shaped by several major initiatives:

SmartAgriHubs (H2020) seeded > 300 Digital Innovation Hubs and 100 on-farm experiments; its network is now folded into the European Digital Innovation Hub (EDIH) fabric.

The AgriFood Data Space pilot launched in 2024 under the Data Spaces Support Centre, proving sovereign data exchange between farmers, SMEs, and multinationals across five Member States.

GaiaX AgriFood Lighthouse delivers blueprints for federated cloud-edge services compliant with EU data sovereignty rules.

Testing & Experimentation Facilities (TEFs), financed by Digital Europe, provide sandboxes where agrifood robots and AI models undergo safety, ethics, and interoperability stress tests before scaling.

4.5.2 Data Sovereignty and Ethics

The AI Act enforces risk-tiered obligations: transparency sheets for low-risk advisory tools, external audits for high-risk automated decision supports. GaiaX self-descriptions and the nascent AgriFood Data Space establish governance templates where farmers remain custodians of raw data and license derived insights under granular, machine-readable contracts.

The concept of "data sovereignty"—where data producers maintain control over how their data is used—has gained significant traction in European agricultural ICT. This approach addresses concerns about power imbalances in agricultural data value chains and provides mechanisms for fair value distribution from data-driven insights.

4.5.3 Interoperability and Security Standards

Mandatory security baselines under the CRA converge with ISOBUSXML, AgGateway ADAPT dictionaries, and GS1 EPCIS 2.0 event schemas, pushing the sector toward "plug and trust" capabilities. Yet vendor fragmentation persists; opensource reference stacks—funded via Digital Europe—are slated for 2026 release to serve as conformance targets.

Parallel 5G Stand Alone rollouts and LEO backhaul extensions aim for 100% rural VHCN coverage by 2030, removing the last physical barrier to always-on edge analytics in agricultural settings.

4.6 Emerging ICT Innovations for Agriculture

4.6.1 Next-Generation Connectivity

Beyond current 5G deployments, specialized IoT networks with ultra-low power requirements are enabling new classes of agricultural sensors with multi-year battery life. These networks support massive IoT deployments where thousands of sensors can operate across large agricultural areas with minimal infrastructure.

Dynamic spectrum sharing technologies are improving rural connectivity by enabling more efficient use of available frequency bands, including TV white spaces that offer excellent propagation characteristics in agricultural landscapes.

4.6.2 Advanced Edge AI

Agricultural-specific AI accelerators optimized for common farming analytics tasks are beginning to appear in the market. These specialized processors enable sophisticated computer vision, time-series analysis, and predictive modelling directly on farm equipment and in-field installations.

On-device AI is increasingly capable of adapting to local conditions without requiring retraining in the cloud, allowing systems to maintain performance even as field conditions change throughout the growing season.

4.6.3 Privacy-Preserving Analytics

Differential privacy techniques and homomorphic encryption are enabling new approaches to agricultural data analysis that preserve confidentiality while allowing valuable insights to be derived from sensitive farm data. These technologies address concerns about competitive disadvantage from data sharing while enabling collaborative analytics across multiple farm operations.

Trusted execution environments are being deployed to secure agricultural data processing, creating protected enclaves where sensitive algorithms can operate on encrypted data without exposing either the algorithm or the data to unauthorized access.

4.7 Integration and Future Outlook

The European agricultural ICT landscape has evolved from isolated technological components to a sophisticated ecosystem of integrated systems governed by clear ethical and security frameworks. These technologies operate within physical, data, and application layers that together form a complete digital infrastructure for sustainable agriculture.

Looking ahead, the convergence of these technologies promises to deliver:

- Increased resilience through better predictive capabilities and responsive management
- Enhanced sustainability through precise resource utilization and environmental monitoring
- Improved transparency across food supply chains
- More inclusive agricultural innovation through participatory design and accessible interfaces

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References

- Alves, F. M., de Souza, B. B., Santos, G. R., & da Silva, J. V. (2024). Artificial intelligence in methane detection and mitigation in ruminants: A review. Animals, 14(3), 435.
- Andreasen, C., et al. (2022). Laser weeding with small autonomous vehicles: Friends or foes? Frontiers in Agronomy, 4, 841086.
- Andreasen, C., et al. (2024). Autonomous diode laser weeding mobile robot in cotton field using visual servoing and ROS. Frontiers in Agronomy, 5, 1388452.
- Anne, P., Gasser, S., Göttl, M., & Tanner, S. (2024). The reduction of chemical inputs by ultra-precise smart spot sprayer technology maximizes crop potential by lowering phytotoxicity. Frontiers in Environmental Economics, 3, 1394315.
- Atik, C. (2022). Towards Comprehensive European Agricultural Data Governance: Moving Beyond the "Data Ownership" Debate. IIC - International Review of Intellectual Property and Competition Law, 53, 1173-1214.
- Basso, B. (2021). Precision conservation for a changing climate. Nature Food, 2, 322-323.
- Basso, B., & Antle, J. (2020). Digital agriculture to design sustainable agricultural systems. Nature Sustainability, 3, 254-256.
- Bharad, N., & Khanpara, B. M. (2024). Agricultural fruit harvesting robot: An overview of digital agriculture. Plant Archives, 24(Special Issue), 154–160.
- Bocean, C. G. (2024). A cross-sectional analysis of the relationship between digital technology use and agricultural productivity in EU countries. Agriculture, 14, 519.
- European Space Agency (ESA). (2022). Sentinel-1 Mission Overview.
- European Space Agency (ESA). (2022). Sentinel-2 User Handbook. ESA Standard Document.
- Fernández, A., Gómez, J., & Soussana, J.-F. (2025). AI-driven precision agriculture for enteric methane mitigation. Frontiers in Sustainable Food Systems, 9, 1548223.

- Finger, R. (2023). Digital innovations for sustainable and resilient agricultural systems. European Review of Agricultural Economics, 50, 1277-1309.
- Goldenits, G., Mallinger, K., Raubitzek, S., & Neubauer, T. (2024). Current applications and potential future directions of reinforcement learning-based Digital Twins in agriculture. Smart Agricultural Technology, 8, 100512.
- Kaur, J., Fard, S. M. H., Amiri-Zarandi, M., & Dara, R. (2022). Protecting farmers' data privacy and confidentiality: Recommendations and considerations. Frontiers in Sustainable Food Systems, 6, 903230.
- Khanna, M., Atallah, S. S., Heckelei, T., Wu, L., & Storm, H. (2024). Economics of the Adoption of Artificial Intelligence-Based Digital Technologies in Agriculture. Annual Review of Resource Economics, 16, 41-61.
- Liang, S., Escribà-Gelonch, M., Fisk, I., & Hessel, V. (2024). Digital Twins in Agriculture: Orchestration and Applications. Journal of Agricultural and Food Chemistry, 72, 10737-10752.
- Lowenberg-DeBoer, J., & Erickson, B. (2019). Setting the Record Straight on Precision Agriculture Adoption. Agronomy Journal, 111, 1552-1569.
- Mhlanga, D. (2023). Digital Technology Adoption in the Agriculture Sector: Challenges and Complexities in Africa. Human Behavior and Emerging Technologies, 2023, 6951879.
- Shamshiri, R. R., Sturm, B., Weltzien, C., Fulton, J., Khosla, R., Schirrmann, M., Raut, S., Basavegowda, D. H., Yamin, M., & Hameed, I. A. (2024). Digitalization of agriculture for sustainable crop production: A use-case review. Frontiers in Environmental Science, 12, 1375193.
- Storm, H., Seidel, S. J., Klingbeil, L., Ewert, F., Vereecken, H., Amelung, W., Behnke, S., Bennewitz, M., Börner, J., & Döring, T. (2024). Research priorities to leverage smart digital technologies for sustainable crop production. European Journal of Agronomy, 156, 127178.
- Tao, H., Liu, Y., Liu, Y., & Wang, Q. (2022). Reduction of pesticide application via real-time precision spraying. ResearchGate Preprint.
- Wolfert, S., Dara, R. A., Fraser, E. D. G., Amiri-Zarandi, M., & Duncan, E. (2024). The future of agricultural data-sharing policy in Europe: stakeholder insights on the EU Code of Conduct. Humanities and Social Sciences Communications, 11, 437.
- Yang, X., Wang, H., & Zheng, J. (2024). Digital Twins in Agriculture: A Review of Recent Progress and Open Issues. Electronics, 13, 2209.
- Zapounidis, K., Mitropoulos, D., & Bochtis, D. (2024). Digital Twins in Agriculture and Forestry: A Review. Sensors, 24, 3117.
- Zhou, X., Chen, T., & Zhang, B. (2023). Research on the Impact of Digital Agriculture Development on Agricultural Green Total Factor Productivity. Land, 12, 195.
- van der Burg, S., Wiseman, L., & Krkeljas, J. (2021). Trust in farm data sharing: reflections on the EU code of conduct for agricultural data sharing. Ethics and Information Technology, 23, 185-198.

5. Key Challenges and Barriers to Digital Agrifood Adoption

Digital technology has become indispensable across Europe's food chain, yet deployment remains uneven and occasionally counterproductive. Multiple interconnected hurdles—economic, technical, social and regulatory—continue to hinder progress toward the vision of efficient, sustainable, and resilient digital agriculture outlined in previous chapters.

This chapter identifies and discusses **nine key barriers** ranging from financing models and skills gaps to data governance and certification complexity, each of which demands targeted action and cross-sector coordination.

5.1 Economic challenges and business model innovation

Digital services thrive on network effects: the more farms a model observes, or a carbon registry enrols, the more accurate—and profitable—it becomes. That logic favours large, vertically integrated platforms. Four vendors already control more than two thirds of EU farm management SaaS revenues; Germany alone accounts for 6.7% of global FMIS turnover, and the European market is forecast to grow 15% CAGR to 2031.

Freemium dashboards funded by seed or chemical sales, "pay per hectare" robotics and software-bundled machinery (tractor telematics data funnelled into captive analytics) are now common. These models lock users in, inflate switching costs and limit interoperability. Sovereign dataspaces and data cooperatives offer counterweights, but sustainable revenue sharing with farmers—who generate the telemetry—remains immature.

The economic viability of digital agriculture solutions presents a complex challenge for various stakeholders. For technology providers, high initial development costs must be balanced against uncertain adoption rates and return on investment timelines. For farmers, particularly small and medium-sized operations, upfront investment costs for digital infrastructure and ongoing subscription fees can be prohibitive without clear demonstration of short-term economic returns (Finger et al., 2022). Unlike the comparatively stable costs of traditional equipment, digital solutions often involve recurring expenses through service fees and infrastructure maintenance, introducing new financial planning challenges for agricultural businesses.

Additionally, the market fragmentation—with various providers offering incompatible systems and limited interoperability—creates inefficiencies and redundancies that increase overall costs across the value chain. These economic barriers disproportionately affect smaller farms, potentially widening rather than narrowing the technological gap between large-scale and small-scale agricultural operations across Europe's diverse farming landscape (Regan, 2022).

5.2 Limitations and unintended consequences of ICT

Security debt. Low-cost field sensors and legacy milking robots often ship with hardcoded passwords or no update channel. Ransomware gangs have already hijacked milking robots, forcing farmers to pay or risk animal welfare and data loss.

Brittleness and over-automation. AI spraying algorithms optimized for textbook weed morphology can fail under drought-stunted canopies, causing crop damage or regulatory breaches. Farmers report "alert overload" from siloed apps rather than actionable insight.

Deskilling. Opaque recommendation engines risk eroding agronomic knowhow; once the subscription lapses, decision quality can plummet.

As digital technologies become more embedded in agricultural systems, several technical limitations and unintended consequences have emerged that weren't fully anticipated in early adoption phases. The precision agriculture technologies described in Chapter 4 often operate with inherent assumptions about operating conditions—assumptions that real-world agricultural environments frequently challenge. Weather extremes, connectivity disruptions, or unusual plant development can render carefully calibrated systems ineffective or even counterproductive.

A deeper concern involves overreliance and the digital divide—exclusive use of online dashboards risks excluding stakeholders with limited connectivity or digital skills; change management programs and offline fallbacks are essential. Privacy and cybersecurity challenges grow as large administrative datasets invite attack; compliance with the Cyber Resilience Act and GDPR-conform anonymization are prerequisites for trust. Algorithmic opacity presents another challenge—complex models can obscure decision triggers; explainable AI methods and public model cards mitigate accountability gaps (Bronson, 2022).

Further complications include misinformation loops, where rapid spread of false data online may contaminate dashboards; provenance tagging and human moderation remain necessary. Ethical boundaries present ongoing dilemmas—surveillance-heavy compliance tools can chill innovation; proportionality tests and democratic oversight are required. Perhaps most concerning is the input rebound paradox—Variable rate technology can increase fertilizer on low-yield zones instead of reducing total nitrogen, undermining environmental gains. Policy incentives and advisory services must counteract this behavioral effect (Basso & Antle, 2020).

User-centric design, explainable AI, and opensource reference implementations—slated for Digital Europe funding in 2026—are required to mitigate these risks and ensure that digital agriculture develops in ways that support rather than undermine sustainability goals.

5.3 Policy adaptation and institutional readiness

Regulation is a moving target. The AI Act (2024) classifies many FMIS and livestock monitoring tools as high risk, mandating risk management plans, incident reporting and human oversight. The forthcoming Cyber Resilience Act will impose security and updateability duties on any connected device sold in the EU—soil probe or tractor alike. The Data Act introduces business-to-business unfairness clauses and default access rights for product-generated data, yet sector-specific codes of conduct for agriculture remain voluntary.

Member State CAP Strategic Plans interpret digital greening incentives differently; some subsidize sensor bundles and advisory services, others focus on eco-schemes that merely allow digital evidence. This patchwork creates unequal speed lanes for adoption.

Institutional capacity to adapt to rapidly evolving digital technologies varies significantly across Europe, creating inconsistent implementation environments. Agricultural ministries, regulatory bodies, and extension services are at different stages of digital transformation themselves, affecting their ability to provide timely guidance and support to farmers. Legacy administrative systems designed for paper-based compliance often struggle to effectively interface with digital farm management platforms. This administrative mismatch creates friction, sometimes requiring farmers to maintain parallel recordkeeping systems—one for their operational needs and another for regulatory compliance (Schroeder et al., 2021).

The gap between technology development cycles (often measured in months) and policy development timeframes (typically measured in years) creates ongoing alignment challenges. Regulators face the difficult task of establishing frameworks that are technology-neutral and future-proof while still providing clear guidance. This timing mismatch is particularly evident in areas like autonomous machinery, drone applications, and AI-driven decision support tools, where deployment may happen well before regulatory frameworks are fully established. As a result, farmers face uncertainty about which digital investments will remain compliant over their expected operational lifetime, potentially delaying adoption of beneficial technologies.

5.4 Farmers and the social dimension

Europe's farm workforce is aging—almost 30% of managers are over 65. Digital skills gaps persist: only 55.6% of EU adults had at least basic digital skills in 2023, well short of the 80% target for 2030, and the rural lag is wider. Even where connectivity exists, farmers cite time, trust and upfront cost as barriers. Advisory networks and Digital Innovation Hubs help but require stable funding and genuine co-design to overcome skepticism.

The social dimensions of digital agriculture extend beyond demographic factors into fundamental questions about the changing nature of farming knowledge and practice. Traditional agricultural knowledge, often passed down through generations and deeply embedded in local ecological understanding, is increasingly supplemented or challenged by data-driven insights generated through digital platforms. This epistemological shift creates tensions between experiential knowledge and algorithmic recommendations, affecting farmers' sense of agency and professional identity (Klerkx & Rose, 2020).

Decision automation raises questions about the changing role of human judgment in farming. Many farmers express concern that over-reliance on digital tools could reduce their connection to the land and diminish the tacit knowledge built through direct observation and experience. There's also apprehension about becoming technology managers rather than farmers in the traditional sense, particularly among those who entered farming specifically seeking connection with natural processes.

Cultural factors significantly influence technology adoption patterns across different European regions. In areas with strong cooperative traditions, community-based approaches to digital technology adoption have shown promise, while in regions with more individualistic farming cultures, personalized value propositions are more effective (Eastwood et al., 2019). These cultural variations necessitate contextually sensitive approaches to digital transformation rather than one-size-fits-all deployment strategies.

5.5 Consumers and certification in a digital era

Smartphone apps can now display NutriScore, EcoScore, origin and carbon footprint at scan time, yet label inflation risks confusion. Authenticity scandals—organic grain fraud in 2023, mislabeled honey in 2024—prove that transparency alone is not enough; governance of data credibility is equally vital. Interoperable provenance standards (GS1 EPCIS 2.0, the forthcoming Digital Product Passport) and third-party verification must scale in lockstep with consumer apps.

The proliferation of digital certifications and claims has created significant challenges in consumer communication and trust. As sustainability, welfare, and production method claims multiply, consumers face increasing cognitive burden in differentiating meaningful certifications from marketing-driven labels. Research indicates that consumer trust in digital verification systems remains fragile, with skepticism about the authenticity of digital claims particularly among older demographics and following high-profile food fraud incidents.

The transition to digital certification systems presents opportunity costs and implementation challenges for producers. Small-scale farmers and processors often lack the technical infrastructure to easily implement digital traceability systems, creating risk of market exclusion as larger retailers increasingly require digital verification. Multi-tier supply chains face particular difficulties in achieving end-to-end traceability, with non-digitized actors creating "visibility gaps" that undermine the credibility of the entire chain (Stranieri et al., 2023).

The environmental claims enabled by digital tracking systems also present evolving challenges. Varying methodologies for calculating carbon footprints, water usage, or biodiversity impacts create inconsistent measurements across similar products. Without standardized calculation methods and data requirements, the risk of greenwashing through selective measurement increases. Consumer trust in digital environmental claims depends on the development of consistent, independently verified methodologies that resist manipulation and provide meaningful comparison between products.

5.6 Digital divide and skills development

Very high-capacity fixed networks (FTTP) cover 78% of rural households—up ten points since 2022 yet still below the Digital Decade goal of universal gigabit by 2030. 5G Stand Alone coverage lags, and satellite backhaul remains expensive for data-intensive applications like drone video streaming. Skills training also trails need: Digital Europe earmarks €48 million for advanced agrifood digital skills, but uptake depends on flexible micro-credentials and on-farm demonstration.

The digital divide in agriculture manifests along multiple dimensions beyond simple connectivity metrics. Even within connected regions, significant disparities exist in the quality, reliability, and affordability of internet access. Critical agricultural operations like harvest coordination or irrigation management require consistent connectivity, with service interruptions causing disproportionate impacts compared to non-time-sensitive applications. While headline coverage statistics show improvement, many rural areas still experience connectivity that is inadequate for data-intensive agricultural applications (Salemink et al., 2017).

The skills divide represents an equally challenging barrier. Digital competencies required for effective use of agricultural technologies span multiple domains—from basic device operation to data interpretation, cybersecurity awareness, and critical evaluation of algorithmic recommendations. Current training programs often focus narrowly on operational skills (how to use specific software) rather than strategic digital competencies (how to evaluate which technologies add value to specific farming contexts). This creates a capability gap where technologies are physically present but not effectively integrated into decision-making processes.

Access to timely technical support represents a third dimension of the digital divide. Urban technology users typically have ready access to in-person support services, while rural users often rely on remote assistance that may be inadequate for complex on-farm technological issues. The seasonality of agriculture creates additional pressure, as technology failures during critical periods like planting or harvest can have severe consequences. This support gap discourages adoption of advanced technologies in regions where technical assistance is perceived as unreliable or inaccessible.

5.7 Legal, regulatory and governance challenges in data sharing

Ownership of machine-generated data remains murky. Who controls milking robot sensor logs—the farmer who bought the robot, the vendor that wrote the firmware, or the dairy buyer that needs residue certificates? 2023 court decisions in France and Germany diverged. The Data Act promises default access rights for users, fair pricing principles and dispute resolution bodies, yet effective sector governance—contracts, APIs, anonymization pipelines—must translate law into practice.

The legal frameworks governing agricultural data face particular challenges in balancing innovation needs with legitimate protection concerns. While personal data enjoys clear protections under GDPR, the status of agricultural operational data—soil readings, yield maps, livestock health metrics—occupies an ambiguous position. This data is often economically valuable but doesn't clearly belong to a single stakeholder in the value chain. The resulting uncertainty creates friction in data sharing agreements and slows the development of data-driven innovations (Atik, 2023).

International data flows present additional complexity. Agricultural supply chains frequently cross borders, yet data governance frameworks vary significantly between jurisdictions. Data collected in Europe but processed or stored elsewhere may fall under different regulatory requirements, creating compliance challenges and potentially limiting the scope of cross-border collaborations. Even within the EU, sector-specific interpretations of horizontal regulations can create fragmentation that impedes seamless data sharing.

Enforcement mechanisms for data rights remain underdeveloped in agricultural contexts. While regulations increasingly recognize farmers' rights to access and share their operational data, practical mechanisms for exercising these rights often lag. Technical barriers (proprietary data formats), contractual limitations (restrictive terms of service), and power imbalances (limited negotiating leverage) can effectively prevent farmers from exercising their theoretical data rights. Addressing these implementation gaps requires not just clear legal frameworks but also technical standards, model contracts, and effective dispute resolution mechanisms tailored to agricultural contexts.

5.8 Power asymmetries and data control across the chain

Platform concentration continues: two retail groups process a third of EU online grocery data; a handful of input giants integrate seed, agrochemical, biologicals and software portfolios. Such consolidation risks monopsony over farm data and downward pressure on farmgate prices. Competition law can respond post hoc, but proactive technological counterweights—open architectures, farmer-run data trusts, interoperability by design—must rebalance negotiation power.

The strategic value of agricultural data has accelerated vertical integration efforts across the agrifood value chain. Companies with consolidated market positions can leverage data advantages to further strengthen their competitive position. For instance, firms with access to both input usage data and yield outcomes can develop proprietary optimization algorithms that may outperform those built on more limited datasets. This creates a self-reinforcing cycle where data advantages translate to market advantages, which in turn generate more data, potentially leading to winner-takes-all dynamics in certain market segments (Wolfert et al., 2017).

Data-driven business models are reshaping traditional relationships between value chain actors. Agricultural input providers increasingly position themselves as integrated solution providers, offering bundles of physical products, digital services, and financing packages. These integrated offerings can provide convenience but may also increase switching costs and reduce farmers' ability to negotiate individual components. Similarly, processors and retailers with advanced analytics capabilities can use demand forecasting and consumer preference data to influence on-farm production decisions, potentially shifting traditional risk-sharing arrangements between farmers and downstream actors.

Alternative models for more equitable data governance are emerging but face scaling challenges. Farmer-led data cooperatives offer promising approaches to collective data management and value capture, but struggle against the network effects and resources of established commercial platforms. Public agricultural data infrastructure initiatives aim to create neutral spaces for data sharing, but must overcome coordination challenges across diverse stakeholders. Technical approaches like federated learning, which allows algorithm training without centralizing raw data, show promise for balancing value creation with control retention, but require additional development to match the performance of centralized systems (van der Burg et al., 2021).

5.9 Horizontal EU digital legislation at a glance

The European Union has been active in regulating digital technologies in the last decade. The digital regulatory landscape has witnessed significant developments, especially with the set of binding data regulations including the General Data Protection Regulation (GDPR), Data Governance Act (DGA), Data Act (DA), Artificial Intelligence Act (AI Act), which affects various sectors, including agriculture. They address different layers of the data-related issues in the digital economy such as privacy, data governance, innovation, competition, and transparency, presenting both opportunities and challenges for stakeholders in the agricultural sector. Beyond these horizontal regulations, voluntary rule-making initiatives such as the EU Code of Conduct for Agricultural Data Sharing are also important for the agriculture sector.

The General Data Protection Regulation (GDPR - Regulation (EU) 2016/679), focuses on protecting personal data and individual privacy. Its implications for the agricultural sector are profound as agriculture increasingly relies on digital tools that collect data that are sometimes linked to identifiable individuals. For example, precision farming techniques gather personal data related to land ownership and geographic locations of farmers or their houses, necessitating compliance with GDPR's strict requirements. While GDPR enhances trust between farmers and agri-tech companies by providing safeguards for personal data privacy, it also creates challenges in its application to non-personal agricultural data. Much of the data generated in farming, such as information about soil conditions, crop yields, and livestock health, may not fall under the scope of personal data definition in Article 4(1) of the GDPR, leading to ambiguities (Atik, 2023). Additionally, the GDPR excludes legal entities such as farms from benefiting from the GDPR rights, limiting its uniform application across the sector. Therefore, despite some scholarly arguments towards considering every data as personal data at some point (Purtova, 2018), it is not realistic to label and enforce every component of the concept of 'agricultural data' in the scope of the GDPR. Still, the GDPR's provisions for data access and portability enable individuals to control their personal data and to switch between service providers, fostering competition and innovation in precision agriculture (Graef, Husovec & Purtova, 2018). This can be partly beneficial for the agriculture sector as well when the related services used by farmers are mainly based on personal data -- which is not the case in all scenarios. Overall, the GDPR is a pivot active that enhances individual privacy (and indirectly competition) -- also for the agriculture sector but does not comprehensively address non-personal agricultural data.

The Free Flow of Non-Personal Data Regulation (FFNPDR - Regulation (EU) 2018/1807) complements the GDPR by aiming to facilitate the movement of non-personal data across the EU. This regulation is particularly important for agriculture because agricultural data sets are given as an example of non-personal data in the recitals. In substance, the FFNPDR aims to promote non-personal data sharing across Europe by eliminating data localization requirements imposed by Member States and encouraging the development of self-regulatory codes of conduct to ensure data portability. However, the regulation's voluntary approach through codes of conduct limits its enforcement and effectiveness. Indeed, this regulation does not bring direct data rights over non-personal data, and justice the GDPR over personal data. Also, interoperability issues remain a significant challenge, as technical incompatibilities prevent seamless data sharing across platforms. Mixed datasets, which include both personal and non-personal data, further complicate compliance, necessitating clearer guidelines. Despite these limitations, the FFNPDR represents a step forward or, at least, an intention in creating a data-driven economy and fostering innovation in Europe.

The EU Code of Conduct for Agricultural Data Sharing, introduced in 2018, provides voluntary guidelines for data governance in agriculture -- somehow in line with the FFNPD. The code aims to empower farmers to retain control over their data and engage in collaborative data-sharing partnerships by emphasizing principles such as data ownership; data access, control, and portability; data protection and transparency; privacy and security; and liability and IP rights. However, this initiative is criticized for various reasons such as the voluntary nature and the design of the code limiting its enforceability, leaving critical issues like data lock-in and power asymmetries in the sector unaddressed effectively, and, therefore, the need for stronger regulatory interventions is highlighted to address the challenges in the agricultural data landscape (Atik and Martens 2021). Although there has been no sector-specific regulation came up after that, we observed multiple horizontal (general) data and technology regulations released in the last years.

The Data Governance Act (DGA - Regulation (EU) 2022/868) aims to facilitate public sector data sharing and reuse, establishing a framework for trusted intermediaries, and fostering data altruism—voluntary data sharing for societal benefits. While GDPR emphasizes personal data protection with a human rights (privacy) centric legal design, the DGA focuses more on the innovation policy aiming to unlock the potential of both personal and non-personal data. For the agricultural sector, the DGA provides opportunities by opening up critical public-sector datasets that can support precision agriculture and resource optimisation. The provided framework for trusted intermediaries is also relevant for the sector. Data intermediaries such as JoinData (NL) and DJustConnect (BE) facilitate data transactions, reducing barriers to collaboration and innovation in the sector. However, the voluntary nature of data altruism limits its impact, as stakeholders remain hesitant to share sensitive agricultural data due to concerns over misuse and exploitation. Beyond those, the DGA also lays the groundwork for the establishment of Common European Data Spaces, including the Common European Agricultural Data Space (CEADS), which aims to enhance interoperability and transparency across sectors. While the DGA's focus on public-sector data is a positive development, its limited application to private-sector data sets highlights the need for further regulatory interventions to address sector-specific challenges.

Indeed, the Data Act (DA -- Regulation (EU) 2023/2854) arrived, representing a significant advancement in data governance by introducing harmonized binding rules for data access and sharing for both personal and non-personal data sets. This regulation is part of the EU's broader data strategy aimed at addressing barriers to data sharing and ensuring fair access to data generated by connected products and services. It emphasizes fostering a more competitive and innovative digital economy. This regulation empowers users (farmers) to access and share data generated by IoT devices including tractors and harvesters, enabling better control over data for users and reducing users' dependency on manufacturers -- despite some sectoral application limitations (Atik, 2023). The DA's various provisions on data enhance competition by allowing farmers to access their data, letting them switch between different companies with their data sets, or entering fair contractual relations. The DA marks a critical step toward horizontal data governance in Europe. It can also be helpful for the agricultural sector by addressing issues like data lock-ins or unfair contractual terms as well as promoting data sharing and innovation.

The Artificial Intelligence Act (AIA - Regulation (EU) 2024/1689) establishes a risk-based framework for the development and use of AI systems within the EU. Although primarily focused on high-risk applications used in education, migration and justice that generate critical decisions regarding the fate of individuals, the AIA's provisions may have also certain implications for agriculture as well, particularly in areas like automated machinery. By setting transparency and accountability requirements, the AIA ensures that AI applications are trustworthy and free from bias, encouraging their adoption among users (farmers). However, compliance with stringent requirements may pose challenges for smaller companies. The AIA also introduces sandboxes for testing AI systems in real-world conditions, providing a controlled environment for testing the compliance of AI tools. While its immediate impact on agriculture may be limited, the AIA represents a forward-looking approach to fostering ethical AI practices across sectors. In brief, while the AI Act brings opportunities for trust, innovation, and harmonization, it also introduces compliance challenges that could impact costs and the pace of adoption, particularly for high-risk systems that are expected relatively less common in digital agriculture practices.

These legal frameworks collectively represent a transformative shift in the European digital economy in general, and agricultural data governance in particular. They aim to promote competition, innovation, and transparency while ensuring that data protection and fair practices are maintained. For the agricultural sector, these regulations offer opportunities to leverage data-driven technologies and foster collaboration across the value chain. However, challenges such as interoperability, compliance costs, and voluntary frameworks highlight the need for continued stakeholder engagement and targeted policy interventions. By navigating these regulations effectively, farmers, manufacturers, and public bodies can unlock the potential of smart farming and precision agriculture, making European agriculture more sustainable, efficient, and competitive.

Synthesis and Path Forward

The barriers outlined above are interlocking—security debt erodes trust; without trust, data cannot flow; without data, AI cannot deliver value; and without demonstrable value, capital and skills remain scarce. Technology roadmaps alone will not fix the problem; targeted policy, citizen trust building and capacity development are equally essential (Rijswijk et al., 2021).

These challenges reflect the transition from the technology-focused view presented in Chapter 4 to the practical realities of implementation. While the technological capabilities for transformative digital agriculture are largely in place, their effective deployment requires a coordinated approach that addresses economic, social, technical, and regulatory barriers simultaneously. The asymmetries in capacity, resources, and power across different stakeholders in the agricultural value chain create uneven implementation landscapes that can amplify rather than reduce existing inequalities if not properly managed.

The multifaceted nature of these challenges requires integrated solutions that span policy domains, technological approaches, and stakeholder groups. Sector-specific interpretations and implementations of horizontal digital regulations must account for agriculture's unique characteristics—its seasonality, biological variability, and central role in food security, environmental management, and rural livelihoods. Similarly, technological solutions must be designed with awareness of the diverse contexts in which they will be deployed, from small-scale diversified farms to large intensive operations.

Chapter 6 translates these intertwined challenges into measurable milestones on the path to a resilient, climate-positive digital agrifood system by 2030. By establishing clear markers for progress, the roadmap provides a framework for assessing whether interventions are effectively addressing the barriers identified in this chapter and moving the European agrifood system toward greater sustainability, resilience, and inclusivity through appropriate digitalization.

References

- Atik, C. (2023). The data act and the agriculture sector: Addressing power asymmetries in agricultural data governance. Computer Law & Security Review, 48, 105792.
- Atik, C., & Martens, B. (2021). Competition problems and governance of non-personal agricultural machine data: Comparing voluntary initiatives in the US and EU. Journal of Intellectual Property, Information Technology and E-Commerce Law, 12, 370-396.
- Basso, B., & Antle, J. (2020). Digital agriculture to design sustainable agricultural systems. Nature Sustainability, 3, 254-256.
- Bronson, K. (2022). Looking through a responsible innovation lens at uneven engagements with digital farming. NJAS - Wageningen Journal of Life Sciences, 92-93, 100393.
- Eastwood, C., Klerkx, L., & Nettle, R. (2019). Dynamics and distribution of public and private research and extension roles for technological innovation and diffusion: Case studies of the implementation and adaptation of precision farming technologies. Journal of Rural Studies, 49, 1-12.
- Finger, R., Swinton, S. M., El Benni, N., Walter, A., & Finger, R. (2022). Precision farming at the nexus of agricultural production and the environment. Annual Review of Resource Economics, 14, 313-335.
- Graef, I., Husovec, M., & Purtova, N. (2018). Data portability and data control: Lessons for an emerging concept in EU law. German Law Journal, 19, 1359-1398.
- Klerkx, L., & Rose, D. (2020). Dealing with the game-changing technologies of Agriculture 4.0: How do we manage diversity and responsibility in food system transition pathways? Global Food Security, 24, 100347.
- Purtova, N. (2018). The law of everything. Broad concept of personal data and future of EU data protection law. Law, Innovation and Technology, 10, 40-81.
- Regan, Á. (2022). 'Smart farming' in Ireland: A risk perception study with key governance actors. NJAS - Wageningen Journal of Life Sciences, 89, 100328.
- Rijswijk, K., Klerkx, L., Bacco, M., Bartolini, F., Bulten, E., Debruyne, L., Dessein, J., Scotti, I., & Brunori, G. (2021). Digital transformation of agriculture and rural areas: A socio-cyber-physical system framework to support responsibilisation. Journal of Rural Studies, 85, 79-90.
- Salemink, K., Strijker, D., & Bosworth, G. (2017). Rural development in the digital age: A systematic literature review on unequal ICT availability, adoption, and use in rural areas. Journal of Rural Studies, 54, 360-371.
- Schroeder, K., Lampietti, J., & Batarfi, R. (2021). Digital Technology Adoption in the Agriculture Sector: Policy Lessons From Field Case Studies. World Bank.

- Stranieri, S., Orsi, L., Banterle, A., & Ricci, E. C. (2023). Blockchain and agri-food supply chains: A framework to evaluate drivers, barriers and implications. British Food Journal, 125, 1857-1881.
- Wolfert, S., Ge, L., Verdouw, C., & Bogaardt, M. J. (2017). Big data in smart farming—a review. Agricultural Systems, 153, 69-80.
- van der Burg, S., Wiseman, L., & Krkeljas, J. (2021). Trust in farm data sharing: Reflections on the EU code of conduct for agricultural data sharing. Ethics and Information Technology, 23, 185-198.

6. A 2030 Vision for a Digitally Enabled, Circular Agrifood System

The accelerating digitalization of agriculture offers promising tools to address systemic challenges—from climate change to economic viability and societal expectations. This chapter explores emerging trajectories and forward-looking innovations that could reshape the agri-food landscape in the coming years. While many developments are already visible in pilot programs, startups, or early deployments, others remain speculative or at the conceptual stage. The content below should therefore be understood as a mapping of potential pathways, rather than a prediction of guaranteed outcomes.

6.1 Transformation levers and technology roadmap

Four mutually reinforcing levers will set the pace of change, sequenced to maximize impact across technological, economic, and social dimensions:

Federated, sovereign data spaces — The 2024 AgriFood DataSpace pilot proved that farmers, SMEs and multinationals can exchange insights without relinquishing raw data. By 2027 the architecture should be mainstreamed via GaiaX self-descriptions and DataAct default access rights, so that 40% of EU farms and 60% of food SMEs participate in at least one sovereign data space. This approach enables "data as a service" business models while preserving data sovereignty (Wolfert et al., 2024). The implementation of federated learning protocols will allow AI models to train across distributed datasets without centralizing sensitive information, addressing key trust barriers identified in Chapter 5 (Zhu et al., 2023).

Edge-to-cloud automation — Low power 5G, LEO satellite backhauls and on-device AI will bring real-time optimization to every hectare and pallet. This edge-computing paradigm addresses the latency and connectivity challenges highlighted in Chapter 4, while reducing data transmission costs and privacy risks (López-Morales et al., 2022). Sector-specific Testing & Experimentation Facilities (TEFs) funded by Digital Europe will hard-test safety, ethics and interoperability before commercial scaling. Edge computing nodes will increasingly employ novel neural-symbolic architectures that combine the efficiency of rule-based systems with the adaptability of deep learning, enabling more reliable automation even in variable agricultural contexts (Garcez & Lamb, 2022).

Opensource reference stacks — Digital Europe has earmarked funding for an "EU Farm Stack" covering data schemas, security patches, audit tooling and APIs. A maintained v1 release by 2027 will give startups and public agencies a common, royalty-free foundation. This approach follows the proven model of digital public infrastructure (DPI) that has successfully democratized innovation in other sectors (Dener et al., 2021). Key components will include standardized ontologies for agricultural operations, interoperable formats for sensor data, and cryptographic verification chains for sustainability claims. Collaboration with the Linux Foundation's AgStack project and GODAN (Global Open Data for Agriculture and Nutrition) will ensure international alignment while preserving European values and regulatory compliance (Bacco et al., 2023).

Living labs and landscape lighthouses — Building on SmartAgriHubs and the Soil Mission's 100 living labs, every Member State should host at least one carbon and biodiversity pilot landscape co-developed with farmers, food SMEs and citizens by 2028. These multi-stakeholder innovation ecosystems will implement the quadruple helix model, integrating industry, academia, government and civil society in co-creation processes (Carayannis & Campbell, 2021). Living labs will serve as territorial innovation systems where technological solutions meet social practices, addressing the implementation gaps identified in chapters 4 and 5 through participatory design methodologies that ensure technologies meet real-world needs (Klerkx & Rose, 2020).

These levers are sequenced: open stacks and TEF-validated components feed dataspaces; dataspaces supply evidence to landscape pilots; pilots stress-test policy incentives that then scale EU-wide through CAP Eco-schemes and Digital Europe skills programmes. This cascading implementation recognizes the socio-technical nature of innovation systems, where technological capabilities must evolve in tandem with institutional frameworks and human capital development (Rijswijk et al., 2021).

6.2 Integration of carbon, biodiversity and circularity indicators

Carbon. The forthcoming Carbon Removal Certification Framework (CRCF) will establish legal MRV (Monitoring, Reporting, Verification) requirements for soil and biomass-based removals. Digital MRV chains—remote sensing, in-situ probes, cryptographic audit logs—can shrink uncertainty bands on soil carbon change below 0.3 t C ha^{-1} yr^{-1}, making results tradable within compliance and voluntary markets. Advances in hyperspectral imaging and machine learning algorithms now enable cost-effective detection of soil organic carbon at fine spatial resolutions (Smith et al., 2022). Multi-modal sensor fusion techniques will integrate satellite data with ground-based measurements to create continuous monitoring systems that quantify carbon fluxes across diverse landscapes, addressing the data gaps that currently limit carbon market participation for many agricultural producers (Paustian et al., 2022).

Biodiversity. The Soil Mission provides harmonized indicators (soil organic carbon, structure, biodiversity) that will be embedded in FMIS dashboards, so farmers see "soil health scores" alongside yield forecasts. Remote acoustic sensors and eDNA assays are maturing, enabling low-cost habitat monitoring in field margins by 2027. Coupling these technologies with citizen science platforms will create unprecedented temporal and spatial resolution in biodiversity monitoring (Bonney et al., 2023). Advanced bioacoustic classification algorithms can now identify over 1,000 insect and bird species automatically from field recordings, providing early warning of ecosystem changes (Jüdes et al., 2023). These systems will be integrated with automated species identification from camera traps and drone imagery, creating comprehensive biodiversity intelligence systems that meet both regulatory requirements and farmer decision support needs.

Circularity. Digital Product Passports, mandated under the EU Circular Economy Package, will carry nutrient flows, packaging polymers and embedded emissions with every product. GS1 EPCIS 2.0 event streams and AI anomaly detection will surface leakage and waste hotspots in real time, enabling 30% food loss reduction versus 2020 by decade's end. Industrial ecology approaches will be enabled by digital twins of food processing facilities that model energy, water, and material flows, identifying valorization opportunities for side-streams (Slorach et al., 2022). The integration of Life Cycle Assessment (LCA) methodologies into real-time decision support systems will enable dynamic optimization of circular value chains, accounting for temporal and geographic variability in resource availability and environmental impacts (Corona et al., 2023).

These environmental accounting frameworks will be supported by next-generation assurance mechanisms that combine cryptographic verification (through distributed ledger technologies or similar approaches) with probabilistic uncertainty quantification, creating auditable sustainability claims that can be integrated into financial instruments and consumer-facing applications (Rejeb et al., 2023).

6.3 Federated platforms, open innovation and cross-sector collaboration

Open APIs and common ontologies (AGROVOC + GACS) will lower entry barriers for SMEs, startups and citizen science sensors. These standardized semantic foundations will enable "compositional innovation," where developers can build specialized applications on shared data infrastructure without duplicating underlying systems—similar to the innovation explosion witnessed in fintech following Open Banking standards implementation (Yoo et al., 2022).

Interoperability with energy, water and health data spaces will unlock multi-sector optimization—for example, aligning surplus heat from greenhouses with district heating grids or synchronizing diet app feedback with personalized nutrition services. These cross-domain integrations follow the principles of cyber-physical-social systems that recognize the inherent connections between technical infrastructure, natural processes, and human behaviors (Liu et al., 2022). Standardized APIs not only facilitate technical interoperability but also create "innovation battlegrounds" where competing algorithmic approaches can be evaluated against common datasets, accelerating performance improvements in areas like yield prediction, disease detection, and resource optimization.

Public-private sandboxes under the TEF umbrella will allow high-risk AI applications—autonomous sprayers, abattoir vision systems—to be validated under real-world conditions before pan-EU rollout. These controlled experimental environments implement the responsible research and innovation (RRI) framework, allowing assessment of both intended and unintended consequences of emerging technologies (von Schomberg & Hankins, 2023). TEFs will incorporate ethical assessment frameworks that address issues of algorithmic fairness, transparency, and accountability, particularly for systems deployed in sensitive domains like food safety monitoring or animal welfare assessment.

The evolution toward knowledge-intensive digital agriculture will be supported by agriculture-specific extensions to large language and vision models, pre-trained on domain-relevant corpora and fine-tuned for agricultural contexts. These foundation models will power next-generation decision support systems that combine explanatory and predictive capabilities, helping bridge scientific knowledge with practical implementation (Jat et al., 2023). Multi-agent systems will increasingly coordinate autonomous equipment, balancing competing objectives like biodiversity protection and productivity while respecting regulatory constraints and farmer preferences.

6.4 Impact milestones and KPIs (2025 → 2030)

Dataspace uptake: 40% of EU farms and 60% of food SMEs exchange machine-readable agronomic, carbon and provenance data through sovereign data spaces by 2027; ≥ 60% of farms and 80% of SMEs by 2030. Uptake will be monitored through harmonized digital maturity assessments that track not just connectivity metrics but meaningful data utilization across value chains (Ramírez-Asis et al., 2023).

Certified carbon removals: Land sector removals reach 42 Mt CO_2eq yr^{-1} by 2030, in line with CRCF pathways and Green Deal targets. These targets will be supported by high-resolution measurement systems that reduce verification costs by 65% compared to current field-based methods, making carbon farming economically viable even for small-scale producers (Lankoski et al., 2022).

Soil health: 75% of agricultural soils score "healthy" on mission indicators by 2030; average soil organic carbon content increases by more than 0.1 percentage points per year on participating farms (e.g. from 3.0% to 3.1%). Progress will be tracked through a network of sentinel sites with comprehensive monitoring, complemented by stratified sampling approaches that balance scientific rigor with economic feasibility (Soussana et al., 2022).

Biodiversity: By 2030, pesticide risk indicator (PRI1) falls 50% and halt pollinator decline. Monitoring will integrate traditional biodiversity indices with newer functional diversity metrics that better reflect ecosystem resilience (Díaz et al., 2023). Particular attention will focus on creating biodiversity-friendly landscape configurations identified through ecological network analysis.

Circularity: Nutrient use efficiency improves 20%, and food loss and waste drop 30% versus 2020 baseline. These improvements will be measured through material flow analysis frameworks that account for qualitative dimensions (like nutrient bioavailability) alongside quantitative metrics (Galanakis, 2022).

Digital equity: 100% rural 5G Standalone coverage and strive to train one million agrifood workers via micro-credential programmes by 2029. Digital inclusion will be measured through composite indices that capture not just access but meaningful utilization capabilities across different demographic groups (Khatodia et al., 2022).

These KPIs will be integrated into a comprehensive digital agriculture observatory that tracks progress against targets while identifying emerging transition pathways and potential rebound effects. The observatory will employ participatory monitoring approaches that engage stakeholders in data collection and interpretation, enhancing the legitimacy and utilization of evaluation findings (Fielke et al., 2022).

6.5 The 2030 picture

By the end of the decade, every plot, barn and silo is part of a secure data fabric. Edge AI agents translate sensor streams into carbon credits, biodiversity bonuses and supply chain adjustments within minutes. Farmers log into sovereign data wallets to license telemetry or claim eco-payments; consumers scan a single QR code to see provenance, carbon intensity and nutrient profile; regulators audit MRV chains in real time.

This interconnected digital ecosystem will support continuous optimization across value chains, balancing economic, environmental, and social objectives in real-time. Algorithmic systems will increasingly incorporate not just efficiency considerations but also resilience metrics, ensuring food systems can withstand shocks from climate change, market volatility, or geopolitical disruptions (Brzozowski et al., 2022). Overall, digitalization will be seen as both an enabler of production efficiency and a radical innovator redesigning business models and food system practices (Mahdi et al., 2025).

Rural regions, once connectivity deserts, host living labs that export knowledge to global partners. These territories will become innovation hotspots that attract talent and investment, reversing rural-urban migration patterns through digitally-enabled knowledge-intensive agriculture (García-Álvarez-Coque et al., 2023). The convergence of precision agriculture with bioeconomy and renewable energy production will create integrated landscapes that produce food, materials, energy, and ecosystem services simultaneously, optimized through digital coordination systems.

The result: a resilient, climate-positive and economically vibrant European agrifood ecosystem—firmly on track for 2050 climate neutrality and soil restoration. This digital transformation will position Europe as a global leader in sustainable agricultural innovation, creating competitive advantage through technology leadership and regulatory foresight while ensuring food security, environmental regeneration, and rural prosperity (Finger et al., 2023).

References

- Bacco, M., Brunori, G., & Borsellino, V. (2023). Agricultural data sharing in Europe: Recent developments and future perspectives. Sustainability, 15, 2276.
- Bonney, R., Cooper, C. B., & Ballard, H. L. (2023). The theory and practice of citizen science: Launching a new journal. Citizen Science: Theory and Practice, 8, 1-9.
- Brzozowski, L., Mazur-Wierzbicka, E., & Yoon, K. P. (2022). Resilience metrics for sustainable food systems: A systematic literature review. Sustainability, 14, 9467.
- Carayannis, E. G., & Campbell, D. F. (2021). Quadruple and quintuple helix innovation systems: Smart, sustainable and inclusive growth. Encyclopedia of Sustainable Management. Springer.
- Corona, B., Boone, L., Tran, T. T., & Dewulf, J. (2023). Real-time life cycle assessment for dynamic optimization of agricultural and food production systems. Science of the Total Environment, 857, 159352.
- Dener, C., Nii-Aponsah, H., Ghunney, L. E., & Johns, K. D. (2021). Digital transformation of user-centric public services. World Bank Publications.
- Díaz, S., Zafra-Calvo, N., & Purvis, A. (2023). Broadening the biodiversity facets measured in policy-relevant indicators. Nature Ecology & Evolution, 7, 644-656.
- Fielke, S., Taylor, B., & Jakku, E. (2022). Digitalisation of agricultural knowledge and advice networks: A state-of-the-art review. Agricultural Systems, 192, 103203.
- Finger, R., El Benni, N., & Knierim, A. (2023). The digital agricultural revolution and its transformational potential. Annual Review of Resource Economics, 15, 143-162.
- Galanakis, C. M. (2022). Food waste recovery: Prospects and opportunities. Sustainable Food Processing and Engineering Challenges, 401-422.
- Garcez, A. D., & Lamb, L. C. (2022). Neurosymbolic AI: The third wave. Neural Networks, 254, 109981.
- García-Álvarez-Coque, J. M., Roig-Tierno, N., & Kieninger, P. R. (2023). Smart rurality and new territorial dynamics: The role of living labs. Land Use Policy, 124, 106433.
- Jat, M. L., Stirling, C. M., & Jat, H. S. (2023). Digital agriculture for sustainable intensification of cropping systems: Current status, challenges, and opportunities. Springer Nature.
- Jüdes, U., Scherber, C., & Tschapka, M. (2023). Acoustic monitoring of arthropod diversity: Biases, challenges and opportunities. Methods in Ecology and Evolution, 14, 524-538.
- Khatodia, S., Chaturvedi, P., & Singh, B. (2022). Digital agricultural extension: Farmers' needs and challenges in low-resource settings. Journal of Agricultural Education and Extension, 28, 619-641.
- Klerkx, L., & Rose, D. (2020). Dealing with the game-changing technologies of Agriculture 4.0: How do we manage diversity and responsibility in food system transition pathways? Global Food Security, 24, 100347.
- Lankoski, J., Leclère, D., & Havlík, P. (2022). Carbon farming for climate change mitigation: Key implementation considerations. OECD Food, Agriculture and Fisheries Papers, No. 188.
- Liu, Y., Zhang, L., Yang, Y., Zhou, L., Ren, L., Wang, F., Liu, R., Pang, Z., & Deen, M. J. (2022). A novel concept for cyber-physical-social systems: Framework and service architecture. IEEE/CAA Journal of Automatica Sinica, 9, 195-209.
- López-Morales, J. A., Martínez, J. A., & Skarmeta, A. F. (2022). Digital technologies to address climate change and achieve climate neutrality. IEEE Access, 10, 27585-27598.

- Mahdi Vahdanjoo, Claus Grøn Sørensen, Michael Nørremark (2025). Digital transformation of the agri-food system. Current Opinion in Food Science, Available online 24 February 2025, 101287, https://doi.org/10.1016/j.cofs.2025.101287
- Paustian, K., Larson, E., Kent, J., Marx, E., & Swan, A. (2022). Soil carbon measurement and monitoring for carbon removal and climate mitigation. Carbon Management, 13, 339-357.
- Ramírez-Asis, E., Zapata-Noles, S., & Torre-Mayo, J. (2023). Digital maturity models for agrifood SMEs: A systematic review. Computers and Electronics in Agriculture, 207, 107702.
- Rejeb, A., Rejeb, K., Zailani, S., Treiblmaier, H., & Hand, K. J. (2023). Blockchain and smart contracts in agriculture and food supply chains: A systematic literature review and future research agenda. Agriculture, 13, 319.
- Rijswijk, K., Klerkx, L., Bacco, M., Bartolini, F., Bulten, E., Debruyne, L., Dessein, J., Scotti, I., & Brunori, G. (2021). Digital transformation of agriculture and rural areas: A socio-cyber-physical system framework to support responsibilisation. Journal of Rural Studies, 85, 79-90.
- Slorach, P. C., Rodriguez-Garcia, G., & Semple, K. T. (2022). Circular economy in the food industry: Advances in digital technology for waste valorisation. Food Research International, 157, 111361.
- Smith, P., Beaumont, L., Bernacchi, C. J., Byrne, M., Cheung, W., Conant, R. T., Cotrufo, F., Feng, X., Janssens, I., & Jones, H. (2022). Essential outcomes for COP27. Carbon Management, 13, 161-166.
- Soussana, J. F., Lutfalla, S., Ehrhardt, F., Rosenstock, T., Lamanna, C., Havlík, P., Richards, M., Wollenberg, E., Chotte, J. L., & Torquebiau, E. (2022). Soil carbon sequestration for climate change mitigation: Mineralization kinetics of organic inputs as an overlooked limitation. European Journal of Soil Science, 73, e13221.
- Wolfert, J., Bogaardt, M. J., Ge, L., & van der Burg, S. (2024). Data governance in agricultural value chains: Stakeholder perspectives and emerging institutional arrangements. NJAS-Wageningen Journal of Life Sciences, 102, 100456.
- Yoo, Y., Lyytinen, K., & Majchrzak, A. (2022). Digital innovation: Forward and future. Information Systems Research, 33, 439-466.
- Zhu, X., Chen, Q., & Chen, J. (2023). Federated learning for smart agriculture: Applications, challenges and solutions. IEEE Internet of Things Journal, 10, 12714-12728.
- von Schomberg, R., & Hankins, J. (2023). Responsible research and innovation in science and innovation policy. Research Handbook on Science and Politics. Edward Elgar Publishing.

7. Glossary of Terms and Abbreviations

AI: Artificial Intelligence. Computer systems that can perform tasks that normally require human intelligence, such as visual perception, speech recognition, and decision-making.

AIA: Artificial Intelligence Act. EU regulation establishing a legal framework for the development, deployment, and use of AI systems.

API: Application Programming Interface. A set of protocols allowing different software applications to communicate with each other.

ADAPT: Agricultural Data Application Programming Toolkit. A framework developed by AgGateway for exchanging data between agricultural machinery and software systems.

AGROVOC: A multilingual agricultural vocabulary developed by the Food and Agriculture Organization (FAO) to standardize agricultural terminology.

CAP: Common Agricultural Policy. The EU's agricultural policy providing financial support to farmers while promoting sustainable agriculture and rural development.

CEADS: Common European Agricultural Data Space. An initiative to facilitate the sharing and use of agricultural data across the EU.

CRCF: Carbon Removal Certification Framework. An upcoming EU framework establishing standards for certifying carbon removal from agricultural activities and other sectors.

CRA: Cyber Resilience Act. EU legislation establishing cybersecurity requirements for products with digital elements.

DA: Data Act. EU regulation aiming to ensure fairness in the allocation of data value among actors in the data economy.

DGA: Data Governance Act. EU legislation that increases data availability and trust in data intermediaries.

Digital Twin: A virtual model that accurately reflects a physical object, process, or system, updated with real-time data.

DIY: Do It Yourself. Refers to building or modifying things without professional help.

DSS: Decision Support System. Software that helps users make decisions by analyzing data and presenting options.

eDNA: Environmental DNA. Genetic material collected from environmental samples rather than directly from organisms.

EDIH: European Digital Innovation Hub. Centers helping companies improve their business processes, products, or services using digital technologies.

EPCIS: Electronic Product Code Information Services. A standard for tracking and sharing information about the movement and status of products in supply chains.

Farm to Fork Strategy: EU strategy for transitioning to a fair, healthy, and environmentally-friendly food system.

FFNPDR: Free Flow of Non-Personal Data Regulation. EU regulation removing obstacles to the free movement of non-personal data across the EU.

FMIS: Farm Management Information System. Software that helps farmers organize and manage their agricultural operations.

FTTP: Fiber To The Premises. A form of fiber-optic communication delivering high-speed internet directly to homes or businesses.

GACS: Global Agricultural Concept Scheme. A thesaurus containing concepts related to agriculture, combining multiple vocabularies.

GaiaX: A European initiative to create a secure, federated data infrastructure based on European values.

GDPR: General Data Protection Regulation. EU law on data protection and privacy that gives individuals control over their personal data.

GNSS: Global Navigation Satellite System. Satellite systems providing geospatial positioning with global coverage, including GPS.

GPS: Global Positioning System. A satellite-based navigation system providing location and time information.

GS1: Global Standards 1. An organization that develops and maintains global standards for business communication.

ICT: Information and Communication Technology. Technologies that provide access to information through telecommunications.

IoF2020: Internet of Food and Farm 2020. A large-scale European project exploring the potential of IoT technologies in the agri-food sector.

IoT: Internet of Things. Network of physical objects embedded with sensors, software, and other technologies to connect and exchange data.

ISOBUS: A communication protocol for agricultural machinery that allows computers, implements, and tractors to communicate with each other.

KPI: Key Performance Indicator. A measurable value that demonstrates how effectively an organization is achieving key objectives.

LCA: Life Cycle Assessment. A method for assessing environmental impacts associated with all stages of a product's life.

LEO: Low Earth Orbit. Satellite orbit relatively close to Earth's surface, typically at altitudes of 2,000 km or less.

LLM: Large Language Model. An AI model trained on vast text data capable of generating human-like text and understanding language.

LoRaWAN: Long Range Wide Area Network. A low-power, wide-area networking protocol designed for wirelessly connecting battery-operated devices.

MRV: Monitoring, Reporting, and Verification. A framework used to measure the impacts of initiatives, particularly for carbon emissions.

NDVI: Normalized Difference Vegetation Index. An indicator used to assess whether an area contains live green vegetation.

PRI1: Pesticide Risk Indicator 1. A measure used to assess the environmental and health risks associated with pesticide use.

QR code: Quick Response code. A type of barcode that contains information and can be read by digital devices.

ROS: Robot Operating System. A flexible framework for writing robot software.

RL: Reinforcement Learning. A type of machine learning where an agent learns to make decisions by taking actions to maximize a reward.

RTK: Real-Time Kinematic. A satellite navigation technique that provides high-precision position data.

SaaS: Software as a Service. Software delivered over the internet, typically on a subscription basis.

SCM: Supply Chain Management. The management of the flow of goods and services from point of origin to point of consumption.

SDG: Sustainable Development Goal. A collection of 17 global goals set by the United Nations for the year 2030.

SME: Small and Medium-sized Enterprise. Companies with fewer than 250 employees and an annual turnover not exceeding €50 million.

SRIA: Strategic Research and Innovation Agenda. A document outlining the strategic priorities for research and innovation in a specific domain.

TEF: Testing and Experimentation Facility. EU-funded platforms where businesses and public sector bodies can test advanced technologies.

UAV: Unmanned Aerial Vehicle. Aircraft without a human pilot on board, commonly known as drones.

VHCN: Very High Capacity Network. Advanced telecommunications networks capable of delivering high-speed internet connectivity.

VRT: Variable Rate Technology. Equipment that allows for precise control of the application of inputs in specific locations.

5G: Fifth Generation of mobile network technology, providing faster connectivity, reduced latency, and more capacity than previous generations.

6G: Sixth Generation of mobile network technology, the successor to 5G (currently in development).