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The role of digitalisation in supporting farmers and strategic policies for food security and sustainability in Europe: A review

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ABSTRACT

Ensuring food security while reducing dependency on agrochemical inputs has become a strategic priority for European agriculture amid climate change, geopolitical instability and environmental degradation. This paper examines the role of digitalisation in supporting sustainable and resilient agri-food systems across the European Union. Drawing upon an extensive literature review, we analyse the current state of agricultural digitalisation, the systematic barriers constraining its uptake, and the effectiveness of key EU policy instruments, mainly the Common Agricultural Policy. Our study shows that several digital technologies, such as precision agriculture, sensor-based monitoring, and decision-support systems that have reached high technological readiness levels, yet adoption remains uneven. In terms of precision agriculture, several technologies exist, including the variable rate technology for crops that can increase wheat production by 1% to 10%, offering savings in nitrogen fertilisation ranging from 4% to 37%. However, there are trade-offs to consider, such as power asymmetries, rebound effects, and a digital divide stemming from uneven digital literacy among farmers. The paper explores three detailed implementation pathways, including mechanisms, resources, feasibility and time horizon. The pathways include 1) EU framework for agrochemical independence and agricultural data digitalisation; 2) CAP Eco-schemes for low-input digitalisation; and 3) Cooperative digital inclusion for small and medium farms. Overall, the findings underscore that only digitalisation is not a panacea, but its contribution to food security depends on governance, inclusive policy design and long-term investment in enabling conditions.

1. Introduction

European farmers, land managers, policymakers, practitioners, and economies face growing pressures to reform agricultural systems in response to overlapping crises: climate change, geopolitical instability, biodiversity loss, and a continued dependence on agrochemical inputs and imports. Moreover, systemic shocks such as the COVID-19 pandemic [152], the war in Ukraine [15,101], and escalating input costs further increase the arguments on food sovereignty and agricultural self-reliance across Europe. Simultaneously, farmer protests in 2023–2024 have exposed deep tensions between sustainability ambitions and economic viability. As a result, the European Commission is urged to position competitiveness as a key element in making certain that the green and digital transitions are viable both socially and economically for farmers [50,59]. It further increases the advocacy of transition toward sustainability [130], driven by an increasing societal and institutional demand for cleaner, more sustainable agricultural models. This model aligns with the previous strategic vision for the EU's agriculture [41], the strategy for resilient energy supply under the REPower EU, the 2025 Vision for Agriculture and Food [50], and Sustainable Development Goals (SDGs).

Agricultural systems are at the core of various sustainability conflicts. They are a major contributor to broader environmental degradation, soil degradation [18,96], and public health outcomes [92,172]. At the same time, they are increasingly vulnerable to changing climate and natural disasters, which directly threaten food security and overall food system [82,90,124,179]. Consequently, food security in the EU has gained attention beyond availability and access. It adopts a

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multidimensional framework encompassing sustainability, resilience, sovereignty, and environmental integrity [25,126,153]. This shift demands that agricultural systems support various sectors such as environmental security (e.g., soil health, biodiversity, water management), economic stability (e.g., input costs, market resilience), social equity (e.g., smallholder inclusion, rural digitalisation), and strategic autonomy (e.g., reduced dependence on agrochemical imports and fossil fuels) [74,83,91].

In response to these pressures, digitalisation is increasingly positioned as a key enabler of sustainable and resilient agriculture within EU strategies and policies, including the post-2023 Common Agricultural Policy (CAP). Digital approaches have been researched in the literature through the lens of precision technologies, sensors, and satellite-based systems that collect data to inform crucial decisions related to planting, fertilisation, and harvesting, thereby improving productivity and food system efficiency [9,147,173]. Precision agriculture has drawn much attention in the literature as one of the most investigated approaches at the farm level [78,114], defined by information-intensive processes that aim to minimise input use and environmental impact while optimising yields [143]. Furthermore, literature on agricultural technologies and digitalisation in localized contexts reported promising outcomes for food security and agricultural sustainability [78,113]. However, little literature exists on power asymmetries associated with digitalisation, such as digital literacy, data interpretation, privacy, cybersecurity, and tools integration [57,104]. For example, studies by John et al. [88] and Metta et al. [116] noted that the more technologies evolve, the gap in digital skills widens, and it requires more nuanced strategies to ensure inclusive digital capacity-building in rural areas. Whereas a separate strand of the literature studies the implementation of the CAP. With a €260 billion allocation for 2023–2027 continues to represent a significant financial lever, its effectiveness in promoting sustainability remains contested. Literature underlines that direct income support under Pillar 1 remains unchanged [11], with limited influence on reducing input dependency. Research has also shown that the CAP has underperformed in encouraging sustainable input use [33], lacks coherence in addressing food security [21], and faces growing tensions in defending measures for sustainability outputs [170]. Beyond financial interventions, there is growing recognition of the need for coherent, enforceable, and data-driven policies to support sustainability transitions. While previous literature highlights the importance of advisory systems and demonstration farms in guiding practice change [66,142], most existing frameworks remain fragmented and lack robust monitoring and enforcement mechanisms. Moreover, extensive literature has assessed individual policy instruments, particularly the CAP, in achieving specific sustainability targets. Several studies have highlighted limitations of the CAP, including its limited effectiveness in reducing agrochemical dependency [33], incoherence in addressing food security objectives [171], and persistent structural barriers to the adoption of sustainable agricultural practices [170].

In parallel, the literature on digitalisation highlights broader issues associated with digitalisation, such as the need for the development of short digital supply chains that feature embedded traceability, sustainability scoring, resource governance, and consumer feedback mechanisms [12,58]. Further studies noted the pivotal role of digitalisation in advancing socio-economic gains [86,87]. This is an established academic debate concerned with preconditions for the transformative potential of sustainable practices, technological advancements, and efficient resource use in fostering economic development, social welfare, and global environmental sustainability [12,54]. Furthermore, there exist academic conversations underscoring the significance of digital tools in resource circularity, such as nutrient recovery [166], smart composting, and AI-powered waste reduction [115], alongside tackling challenges in resource allocation for cleaner production not only on farms but across the entire food value chain. The effort of our paper is to consistently assess the maturity of evidence for these claims, ranging from “mature evidence” to "emerging evidence” and evidence where “gaps remain”.

Despite the growing body of research outlined above, a significant knowledge gap remains in the literature. A) The works on the current state of digitalisation, highlighting the broader framework of agricultural systems and resource governance, rarely have a European focus; thus, we aimed to provide an EU-focused analysis. B) There is a lack of work on systematic barriers to digitalisation in agriculture; and C) the CAP evaluations rarely address either the way in which policy interventions support digitalisation, nor the degree to which tailored and targeted policies depend on robust implementation of digital tools. These knowledge gaps are precisely what we set out to fill, thereby providing an important contribution to the field. More specifically, we address the following three research questions.

RQ1: What are the main factors of success and trade-offs in the current state of digitalisation adoption in European agriculture?
RQ2: What are the technical, economic, social and political/governance barriers for implementing digital technologies in the agriculture sector?
RQ3: What are the policy options and policy shortcomings under the main strategic interventions, including the CAP and other strategies?

In order to answer these research questions, we structure our analysis around the following objectives:

- Assess the current state of digitalisation in the European agriculture, including technologies such as precision agriculture, smart data platforms, and IoT-based monitoring systems in enabling systemic transformation of the agri-food sector.
- Identify key obstacles to food security, particularly those arising from agrochemical dependency and socio-technical limitations.
- Evaluate strategic interventions within key policy instruments, most notably the CAP, in the context of evolving EU agricultural strategies that aim to foster sustainability and resilience while using digital solutions.

Hence, this study offers a novel, EU-focused analysis of agricultural digitalisation that addresses key limitations in the existing literature. Unlike many global or sector-specific assessments, our research provides a rare regional perspective centred on the European Union. We move beyond local empirical studies of the benefits of specific digital tools by providing an overview of the current state of digitalisation and examining the systematic barriers that shape their adoption and effectiveness within EU agriculture. In addition, this study provides a critical evaluation of the relationship between digitalisation and the CAP, an area often overlooked in existing policy analyses, which rarely consider how CAP instruments enable or constrain digital uptake or how effective policy implementation increasingly depends on robust digital infrastructures and interoperable data systems.

2. Methodology

2.1. Review design

This study employs a qualitative, integrative review methodology to examine the intersection of digital adoption, agricultural sustainability, and food security within the European context. A structured literature review was conducted following PRISMA guidelines (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) to ensure transparency, reproducibility, and methodological rigour. The review synthesised evidence on digital agriculture adoption, EU food security strategies, and sustainability transitions. Five countries included in the Nostradamus project (Germany, Serbia, Switzerland, Slovenia, Cyprus) were used as contextual reference points to illustrate the relevance and applicability of findings and no primary empirical data were collected from these sites.

2.2. Information sources

The review drew upon multiple information sources, for instance, academic literature (such as Web of Science and Google Scholar), policy and regulatory documents (from EUR-Lex, European Commission databases, Eurostat, and Horizon Europe project repositories), and grey literature (such as institutional reports, evaluations, project deliverables, and strategic communications). International strategies were consulted to contextualise European findings, but the primary focus remained on EU-relevant sources.

2.3. Eligibility criteria

In this study, the eligibility criteria are divided into the inclusion and exclusion parts. Inclusion criteria comprised peer-reviewed journal articles, policy documents, and grey literature that address digital agriculture, food security, or sustainability within the European context. Eligible publications were required to be written in English, published between 2000 and 2025, and to provide conceptual, empirical, or policy-relevant insights into barriers, enabling conditions, or strategic frameworks for agricultural digitalisation.

Exclusion criteria encompassed non-English publications; studies without a European focus (except for illustrative or comparative purposes); opinion pieces lacking empirical evidence or policy relevance; and publications falling outside the defined timeframe.

2.4. Search strategy

The search strategy used thematic clusters and Boolean operators, including terms such as: "agricultural independence," "EU food security," "digital solutions in agriculture," "dependency on agrochemicals," "EU strategies and policies," "precision agriculture," "obstacles to digital adoption," "socio-economic challenges," "sustainability transitions," and "strategic transformation of agriculture." Searches were conducted in

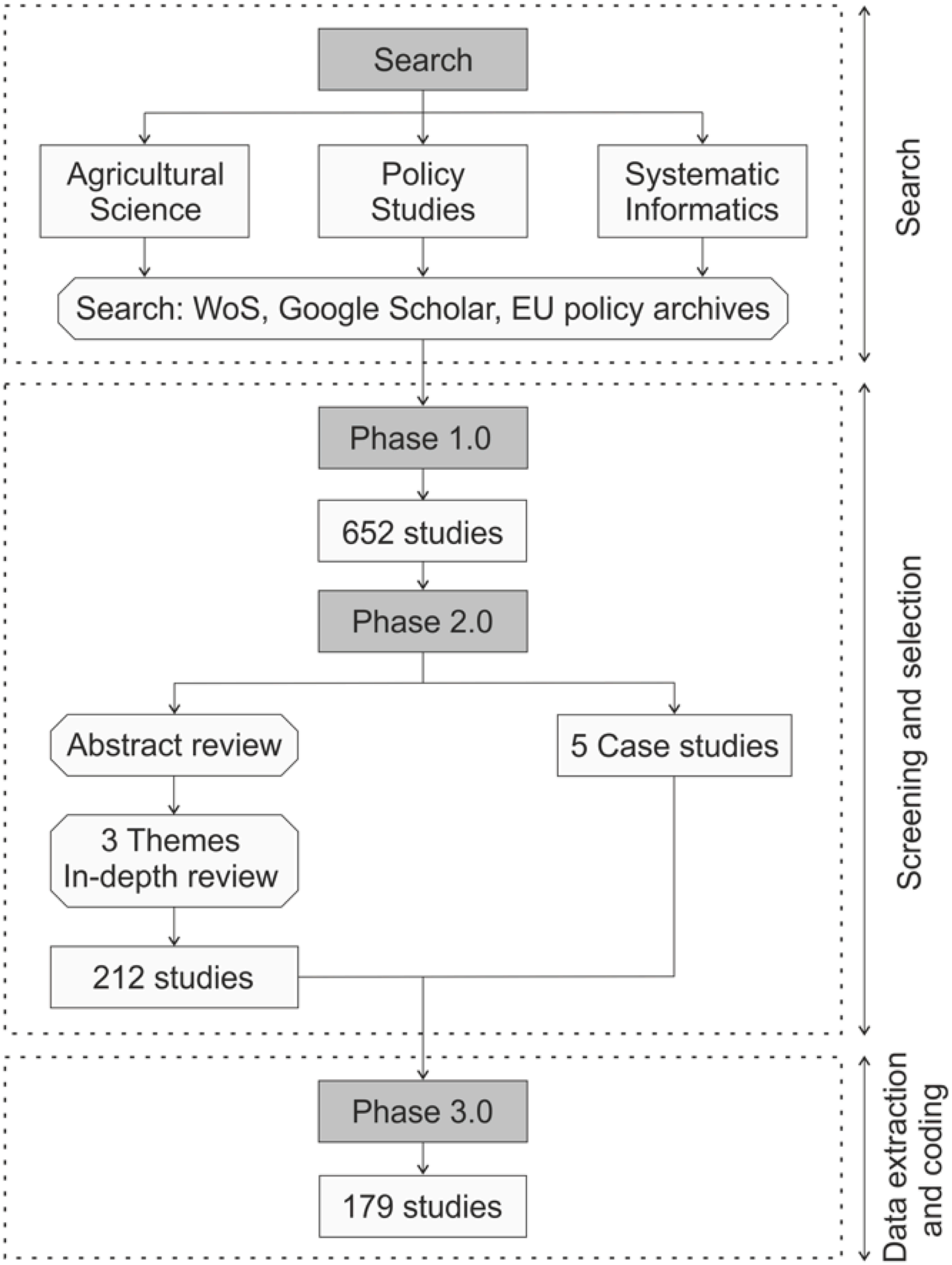

Fig. 1. Methodological approach of the study.

titles, abstracts, and keywords, and were adapted to the conventions of each database.

2.5. Screening and selection process

All identified records were subjected to a two-stage screening process. In Phase 1.0 we conducted the title and abstract screening for relevance to the study objectives; in this phase, we identified 652 studies relevant to the analysis. During this phase, we worked to identify the relevant themes for the subsequent detailed reviews. The themes were identified partly a) based on the frequency of the topic in literature, b) based on the relevance to research questions (RQ1, RQ2, RQ3), and c) based on the relevance for the Nostradamus project. The identification was carried out by an expert panel ($n = 4$). The entries identified were triangulated, and a fifth expert provided validation. In Phase 2.0 we conducted a full-text screening for eligibility according to the criteria above. This screening was guided by the three themes identified in the previous phase. A total of 179 sources were included after screening. Reasons for exclusion at each stage (e.g., irrelevant focus, duplicate records, insufficient detail) were documented. Fig. 1 presents the PRISMA flow diagram summarising the identification, screening, eligibility, and inclusion steps.

As part of Phase 2.0, case studies were sought out in the Nostradamus partner countries, and these case studies were narratively researched (through desk reviews). The sites included are Germany, Serbia, Switzerland, Slovenia, and Cyprus (Fig. 2). Site selection was carried out with reference to the Nostradamus project and was guided by key indicators, such as agrochemical consumption, cereal productivity, digital connectivity, and the educational level of farmers, based on public datasets.

2.6. Data extraction and coding

In Phase 3.0 the structuring was carried out, including data extraction and coding. Data from included sources were extracted into a standardised template capturing publication type, thematic focus, geographic relevance, policy context, and reported barriers or enablers. All documents were analysed using qualitative thematic coding, drawing on grounded theory principles (inductive coding and constant comparison) [24]. The coding was carried out by an expert panel ($n = 4$). The codes were triangulated, and a fifth expert provided validation. The coding framework focused on four main analytical categories: Agricultural and environmental policy instruments; Development and diffusion of digital technologies in agriculture; Structural and socio-economic barriers to transformation; and Alignment with broader resilience and sustainability objectives.

2.7. Synthesis approach

Thematic analysis was conducted through a narrative method [37], which is an appropriate approach for meta-ethnographic studies. Narrative synthesis is the approach to bring together the shared threads and the contradictions found in the relevant literature, thereby furnishing a more complete understanding of the subject matter [37]. In doing so, we have drawn upon the qualitative research already in the public domain (see Section 2.2)

The synthesis was applied to integrate findings across literature, policy documents, and contextual project insights. The analysis was organised around three overarching thematic areas: Theme 1 Current state of digitalisation in agriculture, drawing on European examples; Theme 2 Systematic barriers to digitalisation, challenges in reducing agrochemical dependence, and intersections with sustainability and food security outcomes; and Theme 3 Policy interventions, including the Common Agricultural Policy and relevant regulatory interventions for

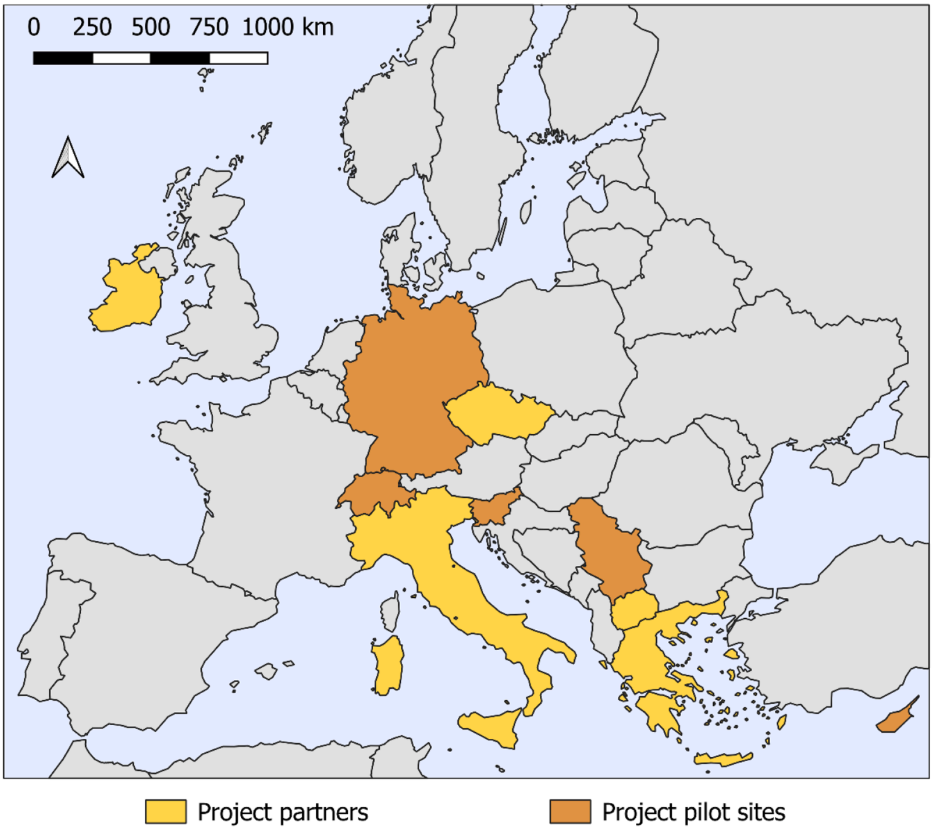

Fig. 2. Geographic focus of case studies.

digitalisation. Finally, we elaborated several implementation pathways, specifying actors, mechanisms, resources, timelines, and political feasibility.

3. Thematic analysis

The thematic analysis is mainly organised into three interconnected sub-sections that together provide a structured examination of digitalisation in European agriculture. Section 3.1 outlines the current state of digitalisation, describing the technologies, platforms, and enabling conditions that shape adoption across the EU. Whereas Section 3.2 describes the systemic barriers that constrain the effective uptake of these tools, considering technical, economic, social, and political/governance dimensions. Finally, Section 3.3 synthesises interventions and pathways that have the potential to address these constraints and support a more sustainable and equitable digital transition. Fig. 3 translates the thematic analysis into a conceptual framework that demonstrates the direction of travel in which digital adoption can contribute to sustainability outcomes in European agriculture through a sequence of interrelated processes. The top layer displays key digital tools, including precision agriculture, IoT technologies, data cubes, and smart supply chains, which generate data and support both farm-level and system-level decision-making. However, their effective uptake is mediated by systemic barriers shown in the second layer, encompassing technical, economic, social, and environmental constraints. Various policy interventions, including the CAP, eco-schemes, digital advisory services, and monitoring systems play a central role in addressing these barriers and enabling the use of digital tools. Moreover, these interactions collectively shape the decision-making of farmers and policymakers, which ultimately influence sustainability outcomes, including food security, climate resilience, biodiversity conservation, and agrochemical dependency. The curved arrows represent feedback loops, highlighting the directionality through which the improved interoperability and data integration would allow for on-farm practices and their outcomes to inform policy design and technological development.

3.1. *Current state of digitalisation in EU agriculture*

3.1.1. *Digital tools and platforms*

Digital tools play a crucial role in terms of facilitating and promoting sustainable and resilient agri-food systems across the EU [174]. A wide range of digital tools, including precision agriculture systems, smart data platforms, IoT-based tools and decision support applications, have been created and are expected to enhance productivity while reducing agrochemical inputs and environmental pressures [38,52]. These technologies also interface with existing policy instruments such as the CAP by monitoring, improving transparency, and enabling targeted interventions. Despite persistent challenges, the EU has developed a set of frameworks and initiatives to advance agricultural digitalisation. The following paragraphs illustrate selected digital tools and platforms, assess their degree of integration with EU policy mechanisms, and highlight existing inconsistencies, efficiency gaps and trade-offs.

Precision agriculture and data-driven management: Precision agriculture (PA), which relies on sensor data, geospatial mapping, and algorithmic analysis, is widely recognised as a strategic enabler for sustainable and resilient agriculture [127,142]. It allows for the site-specific application of inputs, helping reduce agrochemical use while maintaining and improving yields. The main technologies used in

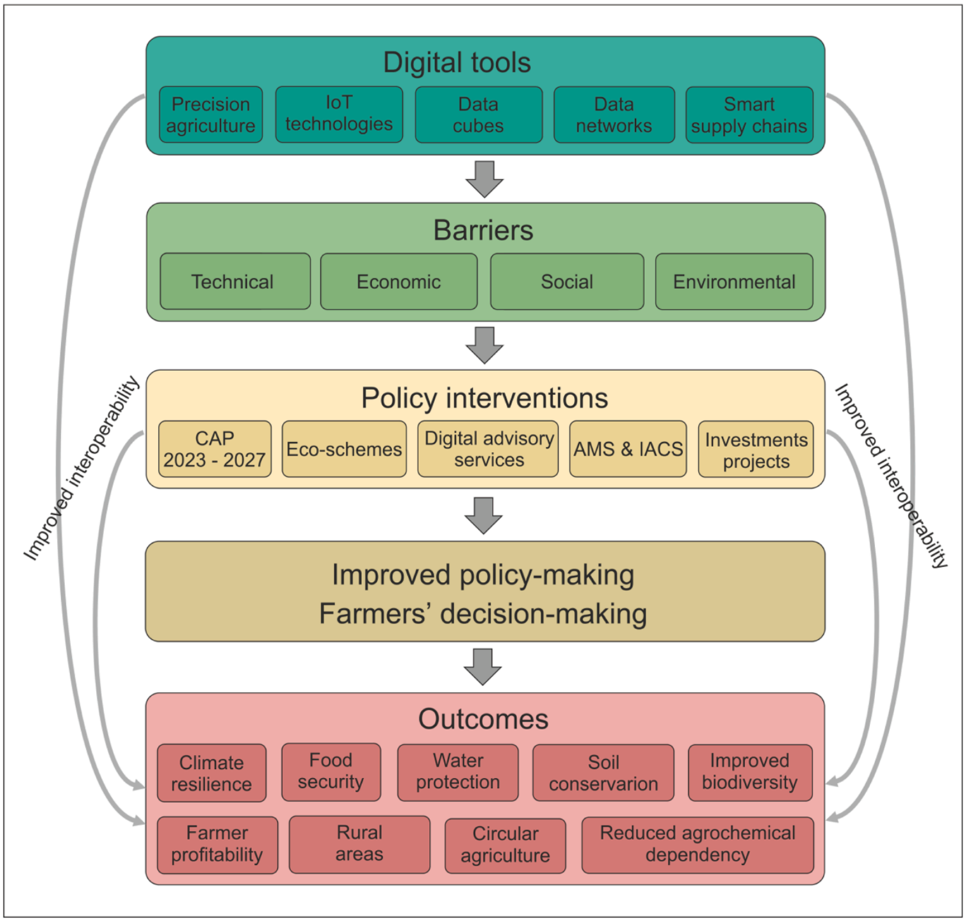

Fig. 3. Conceptual framework illustrating the interaction between digital tools, systemic barriers, and policy interventions in European agriculture, and how these interactions shape farmer decision-making, policy feedback loops, and sustainability outcomes.

PA include satellite guidance for machine ry, drone imaging, animal sensors, telemetry, crop sensors, variable rate technologies and field robotics (Table 1). Evidence is rather mature for significant environmental and economic effects of the majority of PA tools. For example, variable rate technologies can increase wheat production by 1 % to 10 %, offering nitrogen fertilisation savings of 4 % to 37 % [169]. Similarly, Koch et al. [97] demonstrated nitrogen savings of 6 % to 46 % in corn fields. As a result, N_2O emissions can be reduced by up to 34 % in low-yielding areas [160]. Variable irrigation under PF can reduce up to 25 % water usage in agriculture [2]. Satellite guidance systems can help reduce machine time and fuel consumption by 6 % to 11 % [17]. Additionally, optimised route planning and controlled traffic farming reduce soil compaction and can further reduce N_2O emissions significantly [4]. Other greenhouse gas emissions can also be reduced through fuel and fertiliser savings, thus decreasing production-related emissions [7].

However, one of the important factors in implementing digital technologies is economic viability. Farmers tend to adopt digital tools when they expect clear profitability gains, cost savings or improved input-efficiency [183]. Input-saving technologies are still relatively expensive, and the benefits are often low compared to the additional costs. The size of the farm appears to be a decisive factor for success. Evidence is emerging that small farms often struggle, and for these, government grants can help with the acquisition of such tools [128]. For many innovations, especially those that reduce variable costs or labour (e.g. steering systems, automation) rather than merely increasing yield, some evidence suggests that the PA benefits are more predictable, which increases the likelihood of adoption [183]. Lowenberg-DeBoer et al. [106] note that some PA tools, like satellite guidance systems, have been adopted more rapidly, while others, such as variable rate technology applications, are adopted slowly, due to uncertainties in achieving financial payback. More research is needed to address the gaps on economic viability. Furthermore, McKnight et al. [112] argue that trust is another essential element in technology adoption. Emerging evidence shows that early adopters have high levels of general trust while late adopters come with low levels of general trust, leading to greater reliance on expectations and experience. It is therefore critical to continue research on stakeholder engagement during development and testing phases and to utilize partner-growers to demonstrate effectiveness [183].

Moreover, other digital tools such as Farm Management Information Systems are advanced digital platforms designed to collect and use farm data for optimising farm operations [60]. Several smartphone applications were also developed to identify crop diseases and suggest treatments, provide detailed weather information or enable agricultural experts to provide advice on crop management. Additionally, open agricultural digital platforms, based on open-source and collaborative development models, offer more affordable and accessible pathways for a wider range of farmers, including small farms, to adopt digital solutions [123].

However, policy-wise, while the CAP encourages technological uptake through eco-schemes and digital advisory systems, the implementation varies significantly across Member tates. Differences in digital infrastructure investment, training opportunities and advisory capacity contribute to an inconsistent translation of EU-level digitalisation ambitions [10,162]. Furthermore, data fragmentation and lack of interoperability continue to hinder the development of cohesive, farmer-friendly digital ecosystems [53,127].

Data cubes and interoperable platforms: Interoperability is another facilitating condition for the adoption of digital technologies in agriculture, particularly where multiple tools, actors, and data sources must work together in practice. There is a need to consider how new

Table 1

Comparative analysis of current digital tools in European agriculture.

Digital tools	Infrastructure readiness	Policy support	Adoption rates	Barriers by type	Reference
Satellite guidance	TRL 9 - system proven in operational environment	CAP investment measure	Moderate to high: commonly adopted by larger farms	Economic	[111, 133]
Satellite and drone imaging	TRL 9 - system proven in operational environment	CAP investment measure; Farm advisory	Low to moderate: specialised service companies and some large farms	Technical Economic Social	[111]
Telemetry (remote measuring)	TRL 9 - system proven in operational environment	CAP investment measure	Low to moderate: large farms	Technical Economic	[81,111]
Animal sensors	TRL 9 - system proven in operational environment	CAP investment measure	Moderate: adopted by larger farms	Economic	[62]
Crop sensors	TRL 9 – system proven in operational environment	CAP investment measure; Farm advisory	Low to moderate: adopted by some larger farms and service companies	Technical Economic	[106, 133]
Variable rate technologies (VRT)	TRL 9 – system proven in operational environment	CAP investment measure; Farm advisory	Low to moderate: adopted by some larger farms and service companies	Technical Economic	[106, 133]
Field robots	TRL 8 to 9 – some systems proven in operational environment	CAP investment measure; Farm advisory	Very low: leading vegetable farms or pilot farms	Technical Economic Governance Social	[67, 31]
Data cubes and interoperable platforms	TRL 5 – technology validated in relevant environment	Integrated Administration and Control System (IACS) (needs extension for interoperability) - under public funds	Low: most countries struggle with data interoperability	Technical Economic Social Political/ Governance	[13,144]
Digital supply chains and circular resource flows	TRL 2 – technology concept formulated	CAP investment measure for the farmer interface to digital circularity	Low: concept yet to be implemented	Technical Economic Social Political/ Governance	[28,35]

Note 1: coding of TRL follows the Horizon Europe scale [40], see Appendix 1. Note 2: *Mature evidence* found for satellite guidance, satellite and drone imaging, telemetry, animal sensors; *emerging evidence* found for variable rate technologies, field robots, data cubes; and *gaps remain* for digital supply chains. The three evidence categories are coded as follows: *mature evidence* (meta-reviews exist based on more than five studies); *emerging evidence* (more than two studies for at least two continents); and *gaps remaining* (lack of individual studies at least at a country or region scale). Note 3: Barrier types are categorized as "*technical*", e.g. connectivity constraints; "*social*", e.g. small-farm expertise gaps; "*economic*", e.g. high costs; and "*policy/governance*", e.g. insufficient legislation (see details in Section 3.2).

digital solutions interact with existing farming practices, advisory services, and institutional infrastructures, rather than treating technologies as stand-alone innovations. General infrastructure support is therefore required for technologies that interoperate, as fragmented or incompatible systems can increase costs and limit practical uptake [32]. Increased interoperability and complementary systems improve economic profitability [30,154]. The development of interoperable systems requires collaboration and cooperation across the agri-tech industry, and may, in some cases, need policy intervention. Examples of cooperation include the development of standards to ensure that smart devices, such as sensors, are interoperable or “platform agnostic” [183]. In addition to compatibility, the ease of incorporating a new technology or behaviour significantly influences adoption rates. User-friendly interfaces and minimal learning curves have been reported as crucial [94].

For the systematic structuring, harmonisation, and integration of heterogeneous agricultural and Earth Observation (EO) data sources into a coherent, analysis-ready framework, Data Cubes can facilitate the abovementioned interoperability by providing a shared analytical framework in which diverse data sources are aligned along common and temporal dimensions. Rather than functioning as standalone platforms, they primarily operate as enabling infrastructures that support data integration, reuse, and interoperability across existing systems [132]. Evidence is emerging that such approaches could enable spatially explicit and near-real-time analytics, although practical implementations remain limited [120]. Thus far, Data Cubes have not progressed beyond local pilot studies and policy aspirations [23,68]. In Europe, this concept aspires to address existing data fragility [71], though it remains distant from large-scale implementation. These platforms could consolidate inputs from systems like Sentinel-1 and Sentinel-2 (Copernicus), processed through engines such as Open Data Cube, Euro Data Cube, and EarthServer [23,68]. Furthermore, these platforms could support crop classification, soil moisture estimation, and carbon monitoring [34] positioning them as potential tools for sustainability-driven decision-making and policy design in agriculture [157].

However, despite this technological promise, the operational adoption of data cubes in EU agriculture remains highly uneven and shaped by structural, institutional, and governance constraints [175]. In more digitally upfront regions such as Switzerland, Germany highlights how linking sensor arrays (e.g., weather stations, IoT networks) with analysis-ready EO data can support diagnostics, compliance monitoring and early warning systems [3,20]. These examples underscore the importance of interoperable geospatial standards and open APIs, which enable data exchange between public registries and farm management tools [157] and reveal the enabling conditions required for successful deployment. Even in these countries, unintended effects such as data ownership and control, knowledge asymmetry, and urban-rural divide may occur. Furthermore, evidence from digitally lagging countries, such as Cyprus and Serbia, shows more persistent barriers, including technical barriers, such as related to, metadata standardisation, social barriers, such as data literacy, and political barriers, such as lack of institutional coordination [27,144]. Such barriers highlight that Data Cube infrastructures do not inherently guarantee improved decision-making; rather, they depend on technical, social, economic and political success factors, including robust governance frameworks, shared standards, and sustained investment in human and institutional capacity.

While the integration of Artificial Intelligence (AI) can improve predictive capabilities of these platforms [89], it also raises concerns regarding algorithmic transparency, risks for marginalised groups, and farmers' autonomy. These dynamics suggest that digital platforms are embedded within broader socio-technical systems, including power asymmetries, resource inequalities, rebound effects, and institutional readiness [102,139].

Digital supply chains and circular resource flows: Digital technologies offer new ways to track products, improve logistical efficiency, and promote circularity across supply chains. Artificial intelligence further strengthens the digital supply chain by its ability to predict demand-supply imbalances, identify potential loss hotspots, and optimise logistics in the linear scheme, enabling a more circular system [28]. In circular economy applications, AI is used to detect patterns in food surplus or spoilage, highlighting the potential for redistribution or valorisation through composting and bioenergy production [164]. Such systems also support nutrient cycling by integrating data on soil health, crop inputs, and organic waste flows, enabling more precise application of recycled fertilisers and reducing reliance on synthetic inputs.

There is emerging evidence for digital circularity frameworks to unify the available tools into actionable strategies. Digital twins and cloud-based dashboards could help simulate and optimise circular resource flows, further aligning production with environmental goals [73]. In this way, digital platforms may go beyond operational efficiency to enable regenerative practices across agri-food systems, helping reduce losses, enhance resilience, and close material loops [174]. However, the real-world implementation of digital supply chain and circularity solutions remains challenging as they rely on broader socio-technical and institutional conditions. Research gaps remain to give us some understanding of how an effective deployment depends on reliable data infrastructures, interoperability between actors, and alignment of incentives across the supply chain, conditions that are not uniformly present across EU member states. Moreover, literature is still lacking focus on unintended effects, such as when AI-based tools create new dependencies on proprietary platforms, increase concerns about data ownership, unequal access to advanced analytics, and the marginalisation of small and medium-scale farmers unable to participate in such systems [128]. These risks, along with the possibility of rebound effects, highlight that digital circularity is not automatically sustainable. Such trade-offs could occur unless governance structures address power imbalances, ensure equitable access, and mitigate unpredictable environmental or social impacts.

3.1.2. Digital inclusion and capacity

The effective use of digital technologies in rural and agricultural communities depends not only on the availability of technology but also on the capacity to use it efficiently. For digitalisation to be inclusive, it requires digital literacy training, affordable access to technology, and public-private investment in rural connectivity. Digital literacy is thus a central issue for capacity building agenda. Recent iterations of CAP Strategic Plans support Agricultural Knowledge and Innovation Systems and integrate digital skills training into farm advisory services. These systems aim to ensure that farmers can navigate and benefit from smart technologies such as precision agriculture tools, climate forecasting models, and e-commerce platforms [167]. However, consistent evidence shows that effective capacity building must go beyond technical training to include community empowerment and governance literacy and participatory approaches that involve farmers, co-operatives, and local authorities to improve adoption and long-term sustainability [79,163]. As such, recently, the Smart Villages initiative has become an important concept within EU rural policy, also funded from CAP Strategic Plans. The Smart Villages are defined as communities that employ innovative solutions to improve resilience, livelihoods, and services through participatory governance and digital connectivity [184]. The concept links digitalisation with bottom-up rural planning and co-designed innovation that demonstrate how digital tools can reinforce community resilience and local agency [98].

Despite these policy efforts, good deal of studies document that there is a persistent digital divide separating urban and rural populations. This gap is particularly visible in farming communities, where limited infrastructure, low internet penetration, and insufficient digital skills hinder the adoption of smart technologies [39]. In particular, the high costs associated with advanced digital tools, smart machinery, and necessary digital literacy create a digital divide. This makes the technology largely inaccessible to small and medium-sized farms, further consolidating market advantages for larger, capital-intensive operations

[19,39]. These disparities underscore that digital inclusion is shaped by broader socio-economic and institutional factors; without addressing affordability, connectivity, and governance barriers, digitalisation risks amplifying, rather than reducing, structural inequalities across European agriculture.

Table 1 gives an overview of key digital tools currently used or emerging in EU agriculture, including their technology readiness level (TRL), policy support, observed adoption patterns and dominant barrier types. Barrier types were assigned based on a qualitative synthesis of the literature, whereby each technology was classified according to the dominant constraints most consistently identified across peer-reviewed studies, distinguishing technical, economic, social, and political/ governance dimensions. Specifically, the table synthesises published literature to highlight how different technologies face distinct enabling conditions and challenges. The High-TRL tools tend to encounter mainly economic barriers, whereas more complex or less mature tools face a wider set of barriers, such as social and political/governance barriers (see Section 3.2).

3.1.3. Digital adoption in European agriculture

Across Europe, several countries have successfully adopted digital technologies in agriculture, offering lessons on the institutional, infrastructural and socio-economic conditions that shape effective uptake [43,180]. The Netherlands has emerged as a frontrunner in PA, deploying GPS-guided equipment, drones, and soil sensors to optimise input use and enhance productivity. These innovations have reduced fertiliser and pesticide use, increasing crop yields through more precise field management [136,138]. Real-time data analysis of soil and weather conditions has enabled Dutch farmers to make informed, sustainable decisions, demonstrating the value of investing in advanced technologies and providing targeted training to farmers [103].

Similarly, Denmark has achieved notable progress in the uptake of digital tools, including the integration of IoT technologies into the dairy and crop sectors. About 60 % of the Danish farmers reported that PA technology supported lower consumption of pesticides, diesel or fewer working hours [129]. Also, using soil moisture sensors has led to reduction in irrigation water use while real-time livestock monitoring has improved animal health and productivity [5]. These gains have been supported by public–private partnerships, collaborative funding mechanisms and frameworks for disseminating digital practices across rural regions, highlighting the role of institutional coordination and stable investment environments in enabling large-scale adoption.

In Italy, machine learning tools and AI are increasingly deployed in vineyard management to analyse climate and pest data. This has reduced chemical inputs by up to 40 %, improving grape quality and yield stability. Even though initially resistant to AI adoption, it was overcome through government-subsidised training programmes. These programs targeted educational support in integrating digital tools into traditional farming systems [182]. This example highlights the importance of targeted capacity-building and sector-specific support, particularly in contexts with strong traditions of manual or experiential knowledge.

Spain has succeeded in enhancing blockchain implementation in agriculture, focusing on the olive oil supply chain. By improving traceability and standardising blockchain protocols, Spain has improved consumer trust through transparent labelling and streamlined administrative processes [69]. Spain's experience illustrates how digital tools can influence value-chain coordination and governance beyond on-farm production practices.

Overall, these examples demonstrate that the effective use of digital technologies in agriculture is not solely dependent on technological solutions. It further requires broader enabling conditions, such as strong advisory systems, public–private collaboration, investment in digital skills, and a supportive regulatory environment. Importantly, these above cases highlight the context-dependent nature of digital adoption across the EU, asoutcomes observed in digitally advanced countries may not be readily transferable to those with weaker infrastructure, lower digital literacy, or different farming structures.

3.2. Systematic barriers to digitalisation and agrochemical reduction

3.2.1. Technical barriers

Several technological challenges continue to hinder the adoption and effective use of digital agriculture across EU. Key issues include problems with compatibility and interoperability, low rates of digital technology adoption, and inadequate data infrastructure on farms. Additionally, vendor lock-in by large companies and poor adherence to software and data standards impede progress. Rural areas often lack reliable broadband coverage, which is critical for effective digital data use in agriculture [51].

Beyond these foundational technical barriers, technological fragmentation further undermines the effective digitalisation of agriculture and the reduction of agrochemical dependence [8]. The EU agri-tech ecosystem is characterised by a lack of interoperability among digital tools and platforms [80], compounded by the complexity of precision agriculture. In particular, the complex landscape of PA demands tailored advisory collaborating with specific technology providers, which may worsen competition and fragmentation, in comparison with the traditional farm advisories that typically offer comprehensive and impartial advice. Additionally, the diverse range of stakeholders in agriculture, including major players in finance, engineering, chemicals, food retail, industry associations, and niche expert groups, poses another challenge [51]. This complexity is exacerbated by the lack of standardized protocols, which are crucial for interoperability and facilitating effective communication throughout the sector. Farmers thus face compatibility issues when attempting to integrate farm management software, sensor networks, and precision agriculture equipment from different manufacturers [121]. These tools frequently operate on closed, proprietary systems [102], making data sharing and system synchronisation difficult, time-consuming, and costly. Such fragmentation undermines efforts to build comprehensive, data-driven farm operations that could support optimal input use and improved environmental performance. Finally, the use of PA poses the risk of rebound effects [139]. This means that increased efficiency may result in the expansion of farming operations or the intensification of land use, which can negate the original environmental savings.

Additionally, the absence of EU-wide standards for data formatting and system architecture impedes progress toward interoperable solutions such as one-stop-shop platforms and aggregated data ecosystems. As a result, the adoption of advanced technologies such as AI-driven input optimisation, remote diagnostics, and predictive analytics remains slow and limited. Although some open-source and collaborative digital agriculture platforms are under development, their rollout is constrained by inconsistent policy support and limited incentives for private sector participation [146]. Addressing these interoperability constraints will require not only technical standardisation but also policy frameworks that actively promote integration, incentivise open systems, and embed interoperability requirements within CAP digitalisation funding streams. Only through such coordinated efforts, digital tools can be fully leveraged to achieve agrochemical reduction and support long-term food security in the EU. Moreover, the increasing complexity of agri-food data from satellite imagery and in-situ sensors to administrative records and farm-level inputs has underscored the urgent need for interoperable digital infrastructures. Our analysis highlights that although EO data and sensor technologies are maturing rapidly, their fragmented implementation and weak data governance remain major obstacles to scaling digital agriculture.

Furthermore, digitalisation may have trade-offs in power asymmetries, and some farmers may become locked into specific corporate ecosystems. For instance, some machinery manufacturers place legal and digital 'locks' on hardware and software, limiting a farmer's ability to repair their own equipment or use third-party data services. This increases reliance on proprietary products and maintenance contracts [75,76,135]. Data itself often also becomes a commodity. Corporations monetize this aggregated data by developing new products, improving input recommendations, and even engaging in financial speculation, often without the farmer receiving a fair share of the value generated from their own activities [104].

3.2.2. Economic barriers

A critical barrier to reducing agrochemical dependency in the European Union is the structural and economic vulnerability of its agricultural systems [95,109,131]. The EU's historical dependence on imported synthetic fertilisers and pesticides has left the agri-food sector exposed to global supply chain shocks and volatile input prices, particularly in the context of recent geopolitical crises such as the war in Ukraine [29,105]. These dependencies undermine the resilience of farming systems and increase the urgency of shifting toward sustainable input alternatives. Although the EU's Farm-to-Fork Strategy set ambitious targets such as reducing pesticide use by 50 % by 2030, progress has been uneven [178].

However, many farmers remain hesitant to adopt digital solutions aimed at reducing agrochemical inputs, such as AI-based nutrient diagnostics or smart spraying technologies, because of high upfront investment costs and uncertainty about their return on investment [6]. This reluctance is especially pronounced among small and medium-sized farms, which represent the majority of EU agricultural holdings. In these farms, the adoption of digital solutions is likely to be supported by the CAP Strategic Plans measure for Investments. However, primarily due to the significant up-front investment in specialised PA machinery, there are high initial costs, coupled with the potential for insufficient return on investment, that present a challenge to the affordability of digital agriculture technologies [51]. Even though subsidies or support programs are in place, limited access to tailored financing mechanisms and risk-averse investment cultures constrain widespread uptake [14]. Thus, the transition toward digitalised, low-input farming remains economically inaccessible for a significant portion of the farming population. Furthermore, digitalisation may create financial and insurance pressure. For instance, corporate access to detailed farm data enables new forms of risk assessment and financialization. Insurance companies and lenders may use this data to determine eligibility, pricing, or even mandate the use of specific digital tools, adding a layer of non-market pressure on farmers' choices [1,181].

As Europe moves toward reducing agricultural dependency and less reliance on external inputs, tools such as blockchain, the Internet of Things, and artificial intelligence provide the backbone for this change. Specifically, blockchain enables the immutable recording of transactions and material flows. This can make supply chains more transparent and build greater trust among stakeholders [137]. When integrated with IoT sensors and smart tags, it could allow for tracking produce from farm to fork, which might reveal points of waste and potentially lead to opportunities for nutrient recovery. However, concerns regarding the scalability of blockchain technology, along with implementation costs and connectivity issues, remain relevant considerations [150].

3.2.3. Social barriers

Disparities in rural digital infrastructure and literacy present significant challenges to the deployment of digital solutions that support agrochemical reduction and enhance food security [75]. The digital divide between urban and rural regions within the EU remains substantial. According to the European Commission's Digital Economy and Society Index [46,47] while urban areas benefit from nearly universal broadband and 5 G coverage, many rural regions have <60 % coverage, particularly in southern and eastern Member States. This infrastructure deficit limits access to high-speed internet, cloud-based services, and real-time digital tools, making it difficult for rural farmers to engage with data-intensive technologies such as IoT-enabled fertilisation systems or remote crop diagnostics [65,107]. Public initiatives such as the Connecting Europe Facility have attempted to address these disparities, but implementation has been slow and uneven, further exacerbated by fragmented national strategies and weak coordination between EU and local authorities [148].

Compounding these challenges is the persistent digital literacy gap among farmers, particularly older or traditionally trained populations [151]. Many agricultural stakeholders lack the knowledge not only to operate digital devices but also to navigate complex issues such as data privacy, cybersecurity, and regulatory compliance [64,185]. While all Member States use CAP Strategic Plans to provide rural training programs and cover use of advisory services, the quality of measures with regard to digital solutions is often insufficient in scope or poorly adapted to the specific needs of the farming community. As digital technologies evolve, these knowledge gaps continue to widen, limiting farmers' ability to engage with tools designed to reduce chemical inputs and improve sustainability [165].

Furthermore, digitalisation can generate new forms of dependency that risk undermining farmer autonomy and decision-making capacity. Under conditions of algorithmic governance, decisions that were once made by farmers based on their experience, observation, and local knowledge are now increasingly replaced by automated, data-driven recommendations from corporate algorithms [63]. This shift relocates control from the farm to corporate servers, diminishing the farmer's role to that of an executor of programmed instructions [175].

3.2.4. Political/ governance barriers

Despite their intended role, eco-schemes have often continued existing farming practices that have been earlier criticised for vague eligibility criteria and insufficient monitoring frameworks [36]. Difficulties in defining controllable and verifiable metrics for precision-agriculture related commitments have limited the integration of such practices into eco-schemes across EU Member States. For example, the Czech Republic's initial CAP Strategic Plan included an eco-scheme promoting variable-rate fertiliser application, but it was not implemented due to the purpose of PA to stimulate farmer flexibility and the associated challenges in establishing verifiable criteria [117].

Similar difficulties appear in other countries, reflecting a broader lack of targeted policy support for precision agriculture. Regulatory barriers also impede technology adoption: restrictive rules on autonomous field robots confine them largely to research settings, and aerial pesticide application bans limit the operational use of drones in optimising pesticide application [186]. These governance and regulatory constraints contribute to underutilised policy synergies and hinder the broader deployment of advanced digital agricultural technologies.

While digital technologies are promoted with the expectation of better operational flexibility, their implementation have been reported to unwittingly catalyse the proliferation of control-oriented technologies, and thusincrease administrative burden through controls [175]. Deficiencies in the monitoring framework for agricultural policies undermine the effective assessment of agricultural practices, thereby impeding the evaluation of their progress and overall effectiveness. This shortfall is constraining the capacity of European agriculture to achieve a more significant impact on sustainability. Crucially, the European Union has only recently sanctioned the use of its satellite data and information for Aerial Monitoring System (see Section 3.3.1) as the official means for authorising payments to farmers [156].

3.3. Interventions

3.3.1. EU policy interventions and CAP

In 2023, the CAP was reframed based on 2018–2020 European Commission legislation [11,42]. This aimed to align EU agri-food systems with land services needed by citizens and address pressures on agricultural land use [125,159]. The strategic framework and policy context of which the CAP is part is shown in Fig. 3. CAP Strategic Plans are national, encompassing Pillar 1 direct income support and Pillar 2 investments for environmental protection. Pillar 1 introduced conditionality in 2003, linking payments to environmental regulations and good agricultural/environmental condition standards, anchoring sustainability in the CAP [145]. Although sustainable options exist for farmers in the post-2023 policy [16], some scientists believe CAP Strategic Plans have not increased their environmental ambition [141]. The introduction of Pillar 1 Eco-schemes [11] has not decreased the gap between the policy's goals and results on the ground. Specifically, there remains a lack of sustainability indicators enabling effective monitoring and enforcement. Regulation (EU) 2021/2115 mandates the CAP to "foster a smart and resilient agricultural sector". If resilience and food security prevail, sustainability is not fully considered in food provisioning services [99]. The post-2023 CAP Strategic Plans provide mechanisms to align subsidies with sustainability [155]. Eco-schemes increased the ambition of Pillar 1 direct payments; these are fully funded by the EU and voluntary, although some Pillar 1 support is conditional on enrolment [49]. As technical requirements are delegated to Member States, these measures could support PA. Our analysis shows, however, that only Belgium-Flanders, Sweden, and Italy have begun introducing eco-schemes relevant to PA [49]. Thus, these eco-schemes are rare and illustrate uneven potential for digitalisation.

In line with resilience and food security, public funding under CAP Strategic Plans should focus on investments in farm modernisation, innovation, diversification, and new practices [72]. Our analysis of CAP interventions based on Regulation (EU) 2021/2115 concurs with findings that this objective can be met through funding for new technologies, as shown also by ITU & FAO [84]. Digitalisation interventions include: a) investments measure; b) farm advisory services; c) modernization of Integrated Administration and Control System (IACS) through data from the new Area monitoring systems (AMS) and geo-spatial project applications; d) automatic claim system; e) refurbishment of EU statistics via the new Farm Sustainability Data Network; f) refurbishment of monitoring principles into the new CAP Performance Monitoring and Evaluation Network with enhanced reliance on result-based indicators; and g) CAP measures to digitalise agriculture [84]. Specific CAP Strategic Plan funding for digitalisation includes Pillar 1 Eco-schemes (Article 31 of R2021/2115), which may support precision agriculture at the Member State's discretion. Pillar 2 supports farm advisory services, the Farm Sustainability Tool for Nutrients, investments in digital technologies (including precision agriculture, smart villages, and broadband), knowledge exchange, and co-operation (Regulation (EU) 2021/2115).

But implementing these policy interventions alongside digital approaches is not easy. The CAP faces challenges regarding data availability and monitoring. Polakova et al. [145] emphasise the importance of tailored and targeted policies regarding soils, habitats, traditional practices, and climate. For such tailoring and targeting of policy interventions, having an evidence base that is anchored in precise data is paramount. Researchers have pointed out that current data systems are fragmented, incompatible, and lack interoperability between platforms and institutions [68,173]. Farmers often maintain records in various formats, ranging from online tools to handwritten notes, making integration both difficult and time-consuming. Reliable monitoring remains a hurdle due to the limited availability of sensor technologies at the farm level. The IACS is a valuable tool with extensive information; however, it currently lacks the data layers necessary to ensure robust interoperability with farm management information systems on the ground [68,173]. Farmers will need to invest in the digitalisation of their records, while public authorities must provide standardised data formats and ensure interoperability of farm data systems with IACS. It is crucial to leverage existing soil monitoring systems and collections of soil data, as well as to establish better connections between IACS and current satellite mapping technologies (AMS).

Beyond the list of measures of CAP Strategic Plans, it is critical that digital technologies are implemented to improve the effectiveness of policy design to ensure evidence-based policymaking. Digital modalities are crucial to help policy interventions to target specific locations and times, and by allowing for interventions designed to fit the unique characteristics of different places and farms [134]. This is paramount because in the sustainability transitions, utilising practice, result, and result-based indicators is the core of monitoring and verification [26,119]. So far, various monitoring and verification approaches have been developed to assist policymakers and the agricultural sector in setting science-based targets for sustainability, often emphasising practices rather than outcomes [134]. We would argue that the use of digital solutions that integrate diverse datasets and policy compliance monitoring and verification frameworks is crucial for evaluating the result-based indicators and thus the effectiveness of policy design. In the run-up to post-2027 CAP, this policy design must be tailored to suit diverse decision-making contexts, considering pedoclimatic and agroecological conditions as well as different goals, contexts and operational logistics [134,158].

3.3.2. *EU regulatory interventions for digitalisation*

Several EU-level initiatives play an important role in implementing digitalisation in agriculture. RePowerEU was introduced to transition away from fossil fuels and is particularly relevant for agriculture due to the sector's energy dependency and exposure to price volatility [45,176]. By promoting the adoption of renewable energy, energy efficiency, and diversified energy sources, the initiative aims to enhance the resilience of agricultural production systems. Moreover, RePowerEU supports data-sharing frameworks between farmers, policymakers, and research institutions to inform policy targeting and enable energy-related digital tools that can increase farm-level efficiency.

The Data Act further addresses systemic barriers identified in Section 3.2 by clarifying rules for data access, interoperability, and platform governance [22,149]. It aims to reduce vendor lock-in, ensure that farmers retain rights to the data generated on their farms, and facilitate the exchange of information across platforms and institutions. These measures directly target governance and technical constraints that currently limit the integration of farm-level data into decision-support systems and public monitoring frameworks.

In parallel, Horizon Europe funding initiatives advance research and innovation related to precision agriculture, AI applications, and autonomous machinery. Investments in Digital Innovation Hubs and Competence Centres further strengthen the ecosystem for digital agriculture by supporting knowledge exchange, experimentation, and training [89,122].

3.4. *Cross-country synthesis: digital readiness and systemic barriers*

Table 2 highlights case studies of five European countries to demonstrate how food security challenges intersect with digitalisation, systematic barriers, and policy interventions. It offers a relative outlook on how various institutional capacities, infrastructural conditions, and socio-economic contexts shape the feasibility and impact of digitalisation in agriculture. Although all countries express strategic ambitions to integrate digital technology, ranging from precision agriculture to water-efficient farming, progress varies widely due to various challenges. These challenges are due to technical- for instance limited digital literacy, connectivity constraints; social - small farm expertise gaps, demographic pressures, and reliance on imported inputs; economic - high implementation costs, and policy-governance – lacking policy support. By analysing these divergent national contexts, the table emphasises that digitalisation does not directly influence or improve food security, but its effectiveness depends on the alignment between technological readiness, policy frameworks, and local structural conditions. These insights underscore the need for harmonised yet context-sensitive pathways for digital adoption and implementation across EU and non-EU Member States.

A cross-country comparison shows that Germany and Switzerland outperform Cyprus and Serbia primarily due to differences in structural

Table 2
Country-level challenges, barriers and digital readiness (literature-based synthesis).

Food security challenges	Digital readiness & enabling conditions	Dominant systemic barriers (T/E/S/G)	Key policy levers	Implications for digitalisation & food security	References
Germany					
Reducing agrochemical dependence; ensuring sustainable yields under climate pressure	High readiness: IoT, sensors, data-driven systems; strong advisory institutions	**Social:** small-farm expertise gaps; **Economic:** high costs, market volatility	Digital Agenda; National Action Plan on Sustainable Use of Plant Protection Products	Strong infrastructure allows digital tools to support efficient, lower-input production; however, uneven capacity among smaller farms limits system-wide food-security gains	[56,161,168]
Serbia					
Vulnerable to supply chain disruptions; dependence on imported fertilisers & machinery; drought and yield instability	Emerging readiness: Digital Village, EU alignment, irrigation support	**Technical:** import dependency; **Social:** low digital literacy; **Economic:** supply chain vulnerability	National Agriculture & Rural Development Strategy 2024; Digital Village Initiative	Structural constraints hinder adoption, limiting digitalisation's potential to stabilise domestic production and enhance food-system resilience	[44,70,177]
Switzerland					
Maintaining high self-sufficiency; managing rising costs of agricultural inputs	Very high readiness: robotics, satellite imaging, AI; strong public–private partnerships	**Economic:** rising input costs	Agricultural Policy 2022+	Innovation capacity supports resilient, high-quality production, but economic pressures limit scaling of digital tools that could enhance long-term food-system sustainability	[55,93]
Slovenia					
Soil health, erosion risks, ageing workforce threatening future food production capacity	Moderate readiness: PA equipment investments; strong organic farming base	**Technical:** rural connectivity gaps; **Social:** ageing population, labour shortages	Rural Development Programme 2014–2020	Despite supportive policies, demographic decline and infrastructure gaps constrain digitalisation's contribution to sustainable and diversified food production	[110,118]
Cyprus					
Water scarcity; high reliance on imports; climate vulnerability; small-scale and fragmented farms	Low-to-moderate readiness: water-efficient farming, early-stage PA irrigation	**Technical:** weak infrastructure; **Social:** training gaps; **Economic:** high cost of tools	National Rural Development Programme; water-efficient agriculture programmes	Severe resource constraints limit digital tools' ability to enhance climate-resilient production, despite targeted initiatives	[48,140]

and institutional readiness. Germany and Switzerland appear to be benefiting from dense advisory networks, strong public–private innovation partnerships, high digital literacy, and well-developed data infrastructures, all of which enable farmers to operationalise digital tools and translate them into productivity and sustainability gains. Cyprus and Serbia face fundamental constraints, including limited access to broadband, uneven agricultural systems, and reliance on imports. Meanwhile, Slovenia faces demographic decline and gaps in rural infrastructure, which hinder suitable digital adoption.

3.5. *Implementation pathways*

To address the systemic challenges of digitalisation, agrochemical dependency, and food security in European agriculture, this chapter presents three policy scenarios. These scenarios are designed to operationalise the research's core themes by integrating digital tools and platforms, reducing reliance on agrochemical inputs, and strengthening food system resilience. Each scenario aligns with the overarching objectives of the EU Farm-to-Fork Strategy and the CAP Strategic Plans. They form a sequenced and mutually reinforcing framework: (1) EU framework for agrochemical independence and agricultural data digitalisation; (2) CAP Eco-schemes for low-input digitalisation and sustainability; and (3) Cooperative digital inclusion for small and medium farms. Together, these pathways form a sequenced and mutually reinforcing framework that tackles the documented risks of corporate dependency, rebound effects, and uneven digital literacy [76,100]. By doing so, they provide operational insights into how digitalisation can support system-level change and improve coordination in the agri-food sector, in line with the EU's strategic vision for sustainable and resilient agriculture.

3.5.1. *EU framework for agrochemical independence and agricultural data digitalisation*

Strong regulatory intervention is essential to ensure agrochemical independence and mitigate digital lock-ins that disproportionately benefit agrochemical corporations. In the current agricultural landscape, digital platforms centralise critical data within corporate ecosystems [102], providing agrochemical manufacturers and agribusinesses with exclusive access to farm data. This practice diminishes farmers' expertise and limits their ability to independently manage agrochemical inputs [108], undermining the potential for the implementation of sustainable farming practices. These corporations often monetise farm data without providing equitable benefits to farmers [104], leading to a deepening reliance on proprietary systems, analytics, and, in turn, agrochemical products.

Policy scenario: Promote agrochemical independence by securing farmer data rights, ensuring interoperability, and promoting wider access to agricultural data to support sustainable farming practices.

Stakeholders: European Commission (regulation), national CAP authorities, agricultural cooperatives, machinery and data platform providers, insurance and finance actors.

Mechanisms:

- Mandate open APIs (application programming interface) and interoperability standards for agricultural machinery, agrochemical software, and data services.
- Support the creation of independent, farmer-controlled data cooperatives to counter existing power asymmetries and rebound effects.
- Develop certification systems ensuring transparency in agrochemical usage data.
- Limit corporate access to farm data in insurance and finance sectors.

Resource needs: High, due to the need for certification systems, data infrastructure, regulatory enforcement, and investment in farmer-controlled digital tools. Funding will also be necessary to develop interoperable systems that serve as alternatives to proprietary models.

Feasibility: Under the shortage of public funds, interoperable systems may be dependent on private funding and open-source initiatives.

Time horizon: 5–10 years, given the need for infrastructure development and policy harmonisation, alongside long-term investment in both digital tools and regulatory frameworks.

Strategic role: Foundational, agrochemical independence and data interoperability are essential to prevent corporate consolidation in the agrochemical sector. Without these measures, sustainability efforts may inadvertently reinforce the existing power asymmetries, limiting the sustainability outcomes.

3.5.2. *CAP eco-schemes for low-input digitalisation and sustainability*

Digital tools can support sustainability only when incentivised toward measurable reductions in inputs and waste. Precision agriculture may otherwise intensify production or expand land use efficiency, generating rebound effects that undermine climate and biodiversity goals [139]. Current CAP instruments primarily reward practice adoption rather than environmental outcomes [130]. A shift toward performance-based low-input digitalisation offers an avenue to embed sustainability into digital transitions.

Policy scenario: Link public funding to verifiable reductions in fertiliser and pesticide use, water consumption, and waste through digital monitoring.

Stakeholders: DG AGRI, national CAP administrators, advisory services, SMEs supplying digital tools, precision agriculture groups, regenerative and organic farming groups, and environmental monitoring agencies.

Mechanisms:

- Revision of Pillar 1 Eco-schemes to reward quantified input reduction and circular practices (through a task force established across member states to develop Eco-scheme criteria that are controllable and auditable.
- Eligibility restricted to interoperable systems to prevent vendor lock-ins [76]; A step change is needed in refurbishing the CAP Farm Sustainability Data Network, including the newly developed sustainability indicators capturing long-term soil and biodiversity effects, not only short-term optimisation.
- Support for technologies enabling nutrient recovery, smart composting, and digital waste reduction.

Resource needs: Moderate, largely regulatory adaptation and monitoring tools

Feasibility: Moderate; however, public budgets are cash-strapped and reduced for post-2027 CAP

Time horizon: 2–5 years, achievable through CAP reform cycles.

Strategic role: Conditional on Scenario 1; without data availability, policies may be insufficiently targeted. Furthermore, performance-based environmental monitoring could intensify corporate dominance through proprietary tracking systems.

3.5.3. *Co-operative digital inclusion for small and medium farms*

Unequal access to digital tools threatens the reduction of agrochemical use by consolidating the benefits of efficiency and risk management among large, capital-intensive actors. High costs of digital machinery, software subscription models, and specialised knowledge exclude smaller farms and older farmers [19,39]. Sustainability outcomes may be threatened by corporate lock-ins that further intensify inequality by constraining the ability to repair machinery or switch data services [76]. Targeted support is therefore essential to prevent digitalisation from accelerating the structural exclusion of some farms.

Policy scenario: Reduce structural barriers to digital uptake through co-operative infrastructures, open-source technologies, and shared rural advisory systems.

Stakeholders: Member State rural governments, CAP Pillar 2 implementation agencies, farmer co-operatives, education and advisory systems, SMEs and open-source developers, and research.

Mechanisms:

- Engaging farmers by collective procurement and shared use of digital machinery and monitoring equipment financed under CAP Pillar 2.
- Public funding for open-source and cooperative digital tools to counter proprietary dependency.
- Digital Skills Hubs integrated into advisory networks to reduce knowledge asymmetries [102].
- Innovation vouchers to be used to support SMEs and co-operatives in reducing agrochemical use [85].

Resource needs: Moderate to high, depending on collective ownership models and infrastructure deployment.

Feasibility: moderate to low, depending on resource needs; private funding may be needed, due to a shortage of public funds

Time horizon: 1–3 years for training; 3–6 years for infrastructure.

Strategic role: Reinforces Scenarios 1 and 2 by ensuring broad participation and preventing exclusionary effects of digital environmental monitoring and data governance.

The above three implementation pathways form a sequenced policy architecture. Data interoperability creates the institutional conditions for digitalisation. Performance-based eco-schemes then link digital innovation to sustainability outcomes. Finally, co-operative inclusion measures ensure that these benefits are operational in a range of farms, including small and medium businesses. As digitalisation advances, policy must therefore prioritise governance and redistribution alongside innovation to ensure that European food systems remain resilient.

4. Critical synthesis

Our study sought to address a critical challenge related to the effective digitalisation of agriculture in the EU for the purpose of food security, reduced agrochemical use, and agricultural sustainability. The increasing use of digital technologies in agriculture presents both opportunities and systemic risks. Across the thematic analysis, digitalisation is shown to support efforts toward agrochemical reduction and food security by enabling more efficient input use, improved monitoring, and enhanced decision-making, although these effects remain context-dependent. However, the feasibility and benefits of digital tools are shaped by deeper structural, institutional, and political-economic conditions. Beyond incremental efficiency improvements, technologies such as precision input systems, IoT-based monitoring and sensor networks, remote sensing analytics, and smart data platforms increasingly function as infrastructures that shape decision-making, market participation, and resource management in agriculture [61].

The review of current technologies (Section 3.1) shows that digital tools have reached high technological maturity in several areas, particularly precision agriculture applications and sensor-based systems. However, the uneven adoption patterns and early-stage development of data infrastructures, such as interoperable platforms and digital circularity systems, reveal a persistent gap between technological capability and real-world use. These discrepancies are further reinforced by major systemic barriers outlined in Section 3.2. Technical barriers such as lack of interoperability and vendor lock-ins interact with economic constraints, limited digital literacy, demographic pressures, and governance deficiencies. The analysis of policy instruments (Section 3.3) further illustrates this misalignment. While the CAP provides a broad enabling framework for digitalisation, many measures remain fragmented, inconsistently implemented, or insufficiently targeted.

Digital innovations have the potential to reduce input use, support circular resource management, and strengthen climate resilience. However, a purely technology-driven approach may create risk for small and medium farms rather than strengthening resilience due to power asymmetries, reinforcing data dependency, and undermining farmer autonomy through algorithmic decision systems and proprietary infrastructures [63,77,135]. Therefore, the effective use of digital technologies requires strategic interventions that go beyond technology deployment and directly address the political-economic structures shaping how digitalisation is governed, accessed, and valued. These must include an EU framework for agrochemical independence; digitalisation and sustainability; and digital inclusion for small and medium farms as provided in our implemented pathway section (Section 3.5).

5. Limitations and direction for future research

Despite the breadth of this study, several limitations should be acknowledged. First, the review is based exclusively on secondary sources, including peer-reviewed articles, policy documents, and grey literature. Although this approach enabled comprehensive synthesis across diverse domains, it also limits the extent to which we can empirically validate the impacts of digital technologies or the effectiveness of specific policy interventions at the local farm level.

Second, the available evidence on digitalisation in European agriculture remains highly uneven. Member States differ in how they report adoption rates, infrastructural readiness, and policy performance, which constrained our ability to carry out fully comparable cross-country assessments. Several promising tools, such as data cubes, interoperable platforms, and digital circularity infrastructures, are still at early TRLs in many regions, and evidence of their effects derives largely from pilot studies or modelling work. As a result, some findings necessarily reflect emerging trends rather than mature, generalisable outcomes.

Third, while the scenarios developed in this paper provide actionable pathways, they remain conceptual. Their feasibility ultimately depends on political commitment, budgetary allocation, institutional capacities, and negotiation among diverse stakeholders.

Future research should aim to address these gaps. Comparative empirical studies across Member States are needed to evaluate how digital tools perform under different agronomic, socio-economic, and governance conditions. Longitudinal assessments would help determine whether digitalisation reduces agrochemical dependency and food security in practice or whether rebound effects emerge over time. In addition, interdisciplinary research combining agronomy, data science, political economy, and rural sociology would enhance understanding of how power asymmetries, platform dependencies, and market concentration shape digital transitions.

Finally, implementation research is needed to assess how CAP interventions, eco-schemes, and other EU policy instruments can better support inclusive and sustainable digitalisation, particularly for small and medium-sized farms. Such studies would provide the empirical grounding necessary to refine and operationalise the strategic pathways proposed in this paper.

6. Conclusion

European farmers and policymakers are under increasing pressure to integrate digital tools into agricultural systems in response to pressing crises, including climate change, geopolitical instability, biodiversity loss, and reliance on agrochemicals. This study examined the current state of digitalisation in European agriculture, the systemic barriers shaping its adoption, and the policy interventions to ensure that digital tools contribute to food security, reduce agrochemical dependency, and sustainability. Our findings show that while digital technologies such as precision input systems, sensor networks, interoperable platforms, and decision-support tools hold considerable promise, their adoption is constrained by profound technical, economic, social, and political-governance barriers. These barriers reinforce uneven adoption patterns and risk consolidating existing inequalities within the agricultural sector.

The analysis reveals that agrochemical dependency, policy fragmentation, and infrastructural inequality continue to threaten the EU's food security and sustainability goals. However, strategic digitalisation supported by a robust policy framework offers substantial opportunities to mitigate these vulnerabilities and strengthen system resilience. Precision agriculture, data-driven farm management, and interoperable digital platforms not only enhance efficiency and traceability but also reduce input reliance, environmental degradation, and socio-economic disparities. Realising this potential will require integrated action. Policies must go beyond compliance and subsidies to include investments in digital infrastructure, harmonised governance standards, and inclusive capacity-building for farmers. Policy frameworks, including the Common Agricultural Policy, the Data Act, and RePowerEU, provide important foundations for the adoption and effective use of digital tools and technologies but remain only partially aligned with on-farm realities and institutional capacities. Without stronger coordination, interoperability standards, and targeted support for small and medium farms, digitalisation may exacerbate power asymmetries and dependency on proprietary platforms rather than resolve them.

Hence, strengthening policy technology synergies is essential for supporting the adoption of digital agricultural tools. Digital technologies can improve policy monitoring and verification by enabling real-time data transfer linked to sustainability outcomes, offering opportunities to enhance the effectiveness of the Common Agricultural Policy performance assessment. One priority is to refine Pillar 2 land-based measures and align them more closely with result-based schemes that incorporate digital monitoring and verification. Such alignment can support more transparent and consistent implementation of sustainability objectives across the EU. Furthermore, we proposed three implementation pathways that highlight the need for robust data governance, alignment of digitalisation with low-input and environmental objectives, and inclusive digital infrastructures that also support small and medium farmers. These pathways highlight that effective implementation of digital technologies depends not only on deployment but also on reforms in governance, incentives, and institutional design.

Overall, the study underscores that digitalisation is not inherently beneficial; its outcomes depend on how technologies are governed, who has access to them, and how their benefits are distributed. Ensuring that digital agriculture supports a more sustainable, resilient, and equitable food system will require continued research, coordinated policy action, and long-term investment in enabling conditions across the European Union.

Ethics approval and consent to participate

All the procedures performed in the studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee. Informed consent was obtained from all the individual participants involved in the study.

Consent for publication

The participants have consented to the submission of the survey results to the journal.

Declaration of generative AI and AI-assisted technologies

During the preparation of this work, the authors used Grammarly and AI-assisted grammar and language-checking tools in order to identify and correct grammatical errors, improve sentence clarity, and ensure consistency in terminology and style. After using these tools, the authors reviewed and edited the manuscript manually, and all co-authors carefully read and verified the revised text. The authors take full responsibility for the content of the published article.

CRediT authorship contribution statement

Giri Prasad Kandel: Writing – original draft, Validation, Methodology, Investigation, Conceptualization, Resources. **Jana Poláková:** Writing – review & editing, Validation, Investigation, Conceptualization, Methodology. **Pavel Hamouz:** Writing – review & editing, Visualization, Methodology. **Adam Hruška:** Writing – review & editing, Validation, Resources. **Ioannis Varvaris:** Writing – review & editing, Validation, Project administration. **Ioannis Manikas:** Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

All authors have not any actual or potential conflict of interest including any financial, personal, or other relationships with other people or organizations within three years of beginning the submitted work that could inappropriately influence, or be perceived to influence, their work.

Appendix 1. Coding for Technological Readiness Level (TRL)

Level 1: Basic principles observed and reported.
Level 2: Technology concept and/or application formulated
Level 3: Analytical and experimental critical function and/or characteristic proof of concept
Level 4: Component and/or partial system validation in a laboratory environment
Level 5: Component and/or partial system validation in a relevant environment
Level 6: System/subsystem model validation in a relevant environment
Level 7: System prototype demonstration in an operational environment
Level 8: Actual system completed and service qualified through test and demonstration
Level 9: Actual system proven through successful mission operation

Sources: Horizon Europe [40].

Data availability

Data will be made available on request.

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