Bridging the Interoperability Gap in Digital Agriculture: Insights from Policy, Practice, and Standards

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1. Introduction

The digital transformation of agriculture promises to enhance productivity, sustainability, and resilience by unlocking the value of data. However, realising this potential depends on multiple foundational conditions. One of them is interoperability. When devices, systems, platforms, and organisations cannot easily exchange or reuse data, the benefits of digital agriculture remain fragmented and out of reach. To address this, the European Union has developed a comprehensive policy framework, ranging from the European Interoperability Framework (EIF) and the Interoperable Europe Act to the Data Act, that seeks to streamline data exchange across sectors. However, in practice, the agri-food sector faces persistent challenges: from limited awareness of existing policies and regulations to inconsistent use of metadata, unstructured data flows, and siloed service architectures making data inaccessible.

This technical paper summarises findings from a multi-method analysis that investigated the current state of data standards and interoperability in European agriculture. Drawing on stakeholder surveys, legal and policy mapping, and a structured review of agricultural data standards, we identify key gaps between regulatory ambition and field-level realities. The insights presented here aim to inform both policy and practice by highlighting actionable opportunities for improving interoperability in the agriculture sector across technical, semantic, and organisational layers.

2. Methodology

This research utilised a mixed-methods approach to assess the coherence between the European Union (EU) data interoperability policy vision and the situation within the agricultural sector. The methodology integrated comprehensive desk research and empirical data collection to provide robust insights. Desk research involved an in-depth analysis of EU policy frameworks, legislative documents, and communications, as well as sectoral developments relevant to sectoral data standards and interoperability. Empirical data collection was conducted through a structured survey disseminated across diverse groups within the XGain project (n=10), which ensured comprehensive insights from various agricultural use cases and supporting a human-centric perspective.

An evaluative framework was established to systematically compare EU policy ambitions with the agricultural sector's practical realities. This framework focused on three dimensions: stakeholder awareness of EU policies, technical compliance with promoted standards, and the feasibility and perceived value of policy objectives. By examining areas of alignment and divergence, the research offered a nuanced understanding of existing interoperability gaps and potential pathways for improvement.

3. EU Interoperability Framework and Policies

Interoperability refers to the capacity of diverse systems, applications, and devices to function cohesively, despite differences in interfaces, execution, or coding languages, thus promoting collaborative environments (Wegner, 1996). Comprehensive interoperability entails interchangeability, compatibility, and usability across products and services from different brands (Thanos, 2014). According to Crémer, de Montjoye, and Schweitzer (2019), interoperability can be categorised into protocol interoperability (partial interoperability), full protocol interoperability, and data interoperability. Protocol interoperability involves basic compatibility, allowing different products and services to interact harmoniously, while full protocol interoperability ensures deeper integration among substitute services. Data interoperability specifically pertains to continuous, real-time data exchange typically enabled through application programming interfaces (APIs) (Crémer et al., 2019).

Interoperability and technical standards are fundamental to the European strategy for data, facilitating seamless data exchange, fair competition, and enhanced user experiences. The EU has actively pursued interoperability through comprehensive policy initiatives and regulatory frameworks aimed at reducing fragmentation and enabling cross-sector data integration.

The European Interoperability Framework (EIF) elaborates on a multi-layered approach encompassing legal, organisational, semantic, and technical interoperability (European Commission, 2017). Legal interoperability addresses regulatory barriers impeding data sharing and integration across jurisdictions. Organisational interoperability emphasises the alignment of workflows and business processes between different entities. Semantic interoperability ensures consistent understanding and structuring of data across diverse systems, while technical interoperability addresses infrastructure, protocols, and data exchange mechanisms.

The EU has issued several significant regulations and strategic policies to guide interoperability. The Digital Markets Act (DMA), Interoperable Europe Act, and the Data Act each outline specific aspects of interoperability, ranging from ensuring platform contestability[1] to facilitating cross-border public sector cooperation or ensuring interoperability within data spaces. Technical standards play a critical role in achieving interoperability, supported by standardisation bodies such as European Telecommunications Standards Institute (ETSI), European Committee for Standardisation (CEN), and European Committee for Electrotechnical Standardisation (CENELEC). The core objective is to create a level playing field where all digital actors, including small and innovative initiatives, can compete fairly, fostering consumer welfare through dynamic, high-quality digital services at competitive prices. Interoperability is central to this vision: in an ideal digital economy, users should be able to seamlessly choose and switch between tools and services without being locked into a single provider due to technical barriers. This freedom strengthens competition, encourages innovation, and supports a more open and resilient market for all stakeholders.

Despite robust policy and regulatory frameworks, the EU's interoperability landscape continues to face challenges. Persistent fragmentation arises due to varied stakeholder interests, sector-specific demands, and incompatibility between horizontal and sectoral approaches. Addressing these challenges necessitates enhanced collaboration, clearer guidelines, and targeted incentives, fostering coherent and effective implementation of interoperability across sectors, particularly within agriculture.

4. Interoperability in Practice: Gaps Between EU Vision and Agricultural Reality

The EU's vision for interoperability seeks to facilitate a seamless, data-driven, and interconnected digital economy. However, the empirical findings reveal significant gaps between these ambitious policy objectives and current realities within the agri-food sector.

Survey results conducted among XGain project partners (n=10) indicate a notable gap in awareness and practical application of key EU data policies. While the General Data Protection Regulation (GDPR) was recognised by 50% of respondents, awareness of other critical regulations, such as the Data Act, Artificial Intelligence (AI) Act, Data Governance Act, and Digital Markets Act, was considerably lower. Few had heard of sector-specific

[1] Referring to the extent to which emerging firms can gain access to a market and compete on equal footing with incumbent digital platforms. The DMA aims to enhance platform contestability by mandating interoperability, data portability, and fair access rules that are expected to lower entry barriers and tame gatekeeper dominance.

interoperability efforts like DCAT-AP. Remarkably, one respondent from the group reported no awareness of these key frameworks, while another described their understanding as superficial.

Basic practices such as publishing service Uniform Resource Identifier (URI) or using structured metadata were rare. A majority of services relied on unstructured data formats like images, PDFs, or text reports, with limited adoption of semantic standards. A clear example of this practical gap is evident in data management practices. According to the survey, 55.6% of respondents deliver unstructured data, such as raw image files, which poses considerable challenges for interoperability. Only 22.2% deliver semi-structured data, and merely 11.1% employ structured data formats like Linked Open Data. Moreover, adherence to common metadata standards was very limited, with 75% of respondents not using any specific standard.

Technical infrastructure and standard data processing methods also exhibit significant fragmentation. Respondents indicated diverse approaches ranging from edge-based devices such as Raspberry Pi and Nvidia Jetson modules to cloud-based solutions. While such experimentation can stimulate innovation, the absence of standardised or coordinated approaches poses substantial barriers to achieving EU interoperability objectives.

Certification and standardisation efforts are notably underdeveloped, with the survey showing that most respondents have not engaged with public or private certification schemes for their equipment or services. Only one respondent referenced a certification scheme, the "Weidemelk" label.

These findings underscore a disconnect between the EU's horizontal interoperability policy objectives and sector-specific realities. While EU policies advocate for comprehensive metadata standards, semantic vocabularies, and service-oriented architectures, the agri-food sector (at least within our focus group) currently lacks the necessary technical maturity and institutional incentives to implement these effectively. Consequently, the envisioned seamless and competitive digital agricultural market remains fragmented and experimental rather than standardised and interoperable.

Addressing these gaps will require targeted, context-sensitive measures, including domain-specific standardisation, increased stakeholder engagement, practical capacity-building, and clearer legal guidance. Without such strategic actions, the transformative potential of interoperability to drive productivity, innovation, and sustainability in the agri-food sector may remain largely unrealised.

5. Mapping the Standards Landscape

The agricultural sector's data standardisation landscape is complex and fragmented, reflecting both the diverse nature of agricultural practices and the multiplicity of stakeholders involved. An extensive analysis of existing data standards reveals a highly concentrated effort in certain domains, accompanied by significant gaps and underdeveloped areas (See the overview of commonly used data standards in agriculture at Annex 1 below).

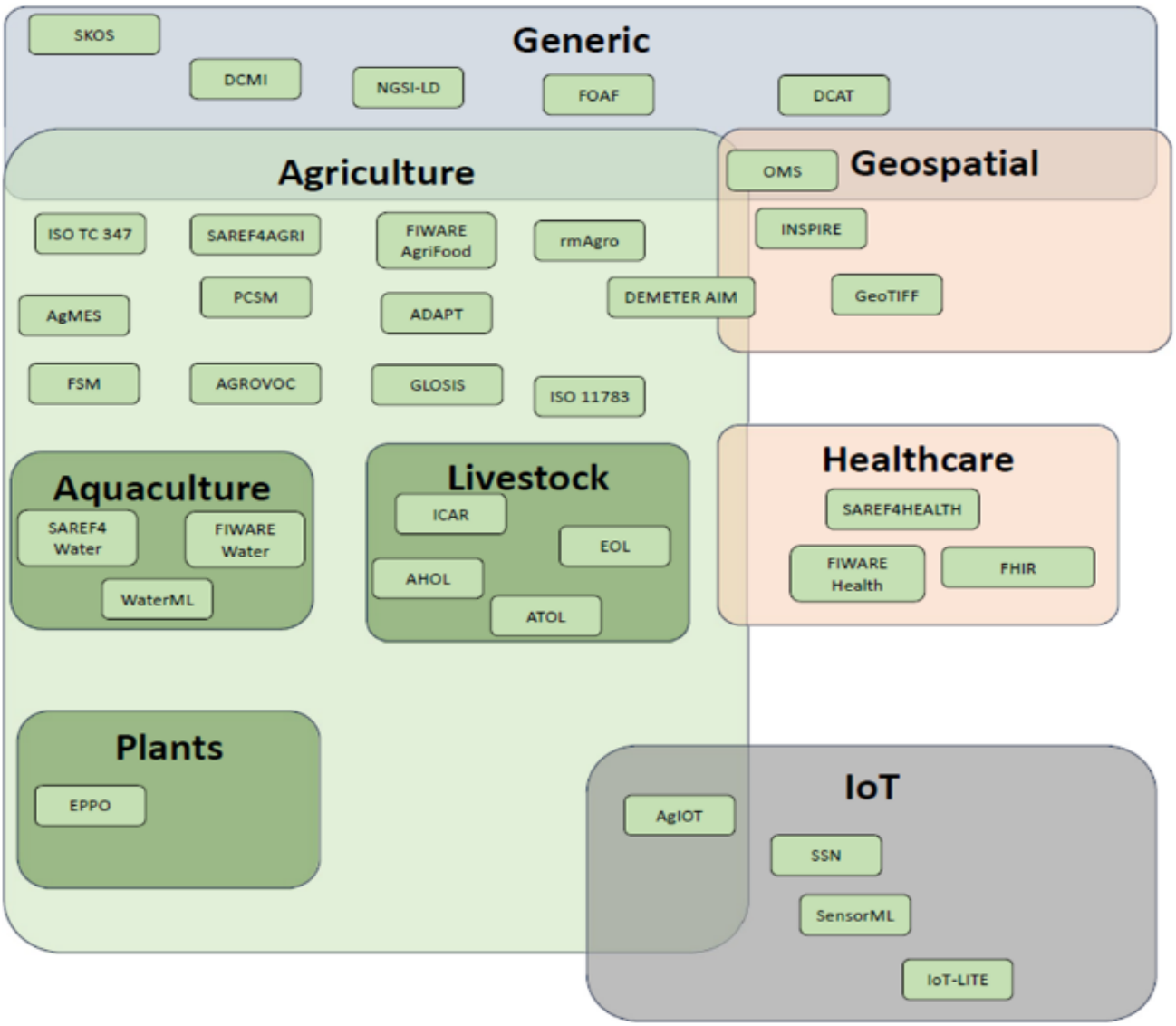
Standards developed by prominent organisations such as FAO, ISO, ETSI, and W3C constitute key reference points within this ecosystem. Notable examples include AGROVOC for agricultural terminology standardisation, DCAT for data cataloguing, and ISOBUS for agricultural machinery interoperability. These standards represent a robust framework aimed at enhancing semantic interoperability and promoting linked open data use across various agricultural contexts.

However, the distribution of these standards across agricultural subdomains remains uneven. While areas such as general agriculture, livestock management, and geospatial applications have a relatively dense concentration of standards, critical domains such as water management, animal behaviour, and AI-driven analytics notably lack

adequate standardisation efforts. For instance, one respondent specifically highlighted the lack of standards for defining animal behaviour and metadata reporting for AI models as significant shortcomings.

Furthermore, the maturity and adoption of standards vary widely. While AGROVOC and DCAT have achieved broad acceptance, many domain-specific standards remain underutilised or are still in developmental stages. Standards such as AgIoT and rmAgro, though promising, are currently under development, limiting immediate practical application and widespread adoption.

Figure 1 – Sectoral Data Standards



The visual mapping (Figure 1 above) clearly illustrates these sectoral data standards. This visualisation underscores the urgent need for harmonisation and coordination to bridge existing gaps and fully leverage the potential of digital agriculture.

Ultimately, this fragmented standards landscape presents both opportunities and challenges. While the existing frameworks provide a valuable foundation for further development, significant efforts are required to foster greater standardisation, coherence, adoption, and integration across the agricultural sector.

6. Recommendations for Enhanced Interoperability

To bridge the existing interoperability gaps and leverage the full potential of digital agriculture, targeted recommendations are proposed for both policymakers and sectoral stakeholders.

For Policymakers:

1. Prioritise domain-specific and cross-domain standardisation: Focus on funding and policy efforts on developing and promoting standards tailored specifically to agricultural practices and challenges.
2. Enhance stakeholder capacity-building: Provide targeted training programs and resources to improve technical skills and knowledge around interoperability standards and frameworks.
3. Foster incentive-driven compliance: Align agricultural subsidies and incentives, such as those under the Common Agricultural Policy (CAP), with adherence to standardised data practices and interoperability frameworks.

For Sectoral Stakeholders:

1. Agree and adopt minimal metadata standards: Start with basic frameworks like Dublin Core and DCAT to improve immediate interoperability and data discoverability.
2. Engage in standardisation initiatives: Actively participate in standard development processes and communities of practice, such as JoinUp, to ensure practical, context-relevant standard creation.
3. Prototype and promote modular architectures: Develop and implement modular, standards-ready architectures that facilitate easier integration and scalability across different agricultural applications.

These recommendations provide a practical roadmap for aligning sector-specific practices with broader EU interoperability frameworks, ultimately fostering a more integrated, productive, and innovative digital agricultural landscape.[2]

7. Conclusion

In conclusion, achieving effective interoperability in digital agriculture is crucial yet challenging. The analysis highlights significant gaps between the ambitious interoperability vision promoted by the EU and the current realities within the agri-food sector. Despite comprehensive frameworks and policies, the practical implementation of agricultural standards remains inconsistent and fragmented.

To address these challenges, targeted actions focusing on enhancing awareness, improving technical infrastructure, and fostering robust standardisation practices are essential. Policymakers and sectoral stakeholders must collaboratively prioritise context-specific solutions, capacity-building, and incentive-driven compliance to realise the full potential of digital interoperability.

Ultimately, bridging these gaps will not only enhance productivity and sustainability but will also strengthen innovation and competitiveness in Europe's agricultural sector, positioning it effectively for future growth and resilience.

[2] Due to the limited scope of this technical paper, a comprehensive exploration of the recommendations is not possible here and should be addressed in a more in-depth follow-up study.

ANNEX 1 - Overview of commonly used data standards in agriculture

Standard	Organisation	Description	Link	Domain	Latest version
ADAPT	AgGateway	The ADAPT Standard is a data schema and set of definitions for the business-to-business transfer of agricultural production data, designed as a standalone data format without software dependencies, succeeding the AgGateway ADAPT Framework.	The ADAPT (A Decentralised Application Programming Toolkit) Framework | ADAPT Framework	Agriculture	2025
AgIOT	INESC TEC	This open source IoT solution is interoperable with ISOBUS and FIWARE standards and portable solutions for different context applications within agrifood.	AgIoT – IoT solution for Agrifood Sector – Modular and interoperable with ISOBUS and FIWARE (inesctec.pt)	Agriculture	Under development
AgMES	FAO	Agricultural metadata element set (AgMES) aims to improve interoperability for different types of information resources in the domain of agriculture.	AgMES 1.1 Namespace Specification | AIMS (fao.org)	Agriculture	2010
AGROVOC	FAO	AGROVOC is a publicly available Linked Open Data resource that standardises agricultural concepts to enhance multilingual data access, indexing, and search efficiency across domains.	AGROVOC: AGROVOC: Alphabetical index: (fao.org)	Agriculture	2025
AHOL	INRAE	Animal health ontology for livestock	Ahol – Livestock Ontologies (atol-ontology.com)	Agriculture - Livestock	2024
AIM	OGC	The DEMETER Agriculture Information Model (AIM) is the common vocabulary in DEMETER project providing the basis for semantic interoperability across smart farming solutions	https://w3id.org/demeter/agri	Agriculture	2023
ATOL	INRAE	ATOL is a machine-readable ontology that generically defines livestock phenotypic traits in context, supporting data integration, measurement alignment, and use across research, education, and animal production.	ATOL (inrae.fr)	Agriculture - Livestock	2025

Standard	Organisation	Description	Link	Domain	Latest version
NGSI-LD	FIWARE/ETSI	The ETSI Industry Specification Group on Context Information Management aims to enhance interoperability among various systems by providing formal definitions and an API (NGSI-LD) for the effective exchange and management of context information across diverse applications and sectors.	https://www.etsi.org/deliver/etsi_gr/CIM/001_099/056/01.01.01_60/gr_CIM056v010101p.pdf	General	2025
DCAT	W3C	The Data Catalogues (DCAT) is an RDF vocabulary that ensures interoperability between data catalogues	Data Catalog Vocabulary (DCAT) - Version 2 (w3.org)	General	2024
DCMI standards	DCMI	The Dublin Core Metadata Initiative (DCMI) develops and promotes metadata standards to support the discovery and management of digital resources. It is best known for the Dublin Core, widely used for resource description across the web.	DCMI: DCMI Metadata Terms (dublincore.org)	General	2020
EOL	INRAE	Environment and rearing system ontology for livestock animals dedicated to production, including fish	EOL (inrae.fr)	Agriculture - Livestock	2025
EPPO standards	EPPO	European and Mediterranean Plant Protection Organisation (EPPO) provides a global database with all pest-specific information that has been produced or collected by EPPO.	EPPO Databases	Agriculture - Plants	2025
FHIR	HL7	Fast Healthcare Interoperability Resources (FHIR) is a standards framework that combines HL7 standards and web standards with a focus on implementability.	https://hl7.org/fhir/summary.html	Health	2023
FIWARE (Agrifood, Health, Robotics)	FIWARE	A joint collaboration program led by the FIWARE Foundation, IUDX, TM Forum, and OASC aims to promote the adoption of compatible common data models to create a digital market of interoperable smart solutions across various sectors.	https://github.com/smart-data-models	General	2025
FOAF	FOAF	Friend Of A Friend (FOAF) is a dictionary of named properties and classes to link people and information using web technologies.	FOAF Vocabulary Specification (xmlns.com)	General	2014

Standard	Organisation	Description	Link	Domain	Latest version
FSM		The Farm Topia Semantic Model (FSM) further develops the Pluotos Semantic Model (PCSM).	https://gitlab.com/Farmtopia/farmtopia-semantic-model/-/tree/main?ref_type=heads	Agriculture	Under development
GeoTIFF	OGC	GeoTIFF is a standard based on the TIFF format and is used as an interchange format for georeferenced raster imagery.	https://docs.ogc.org/is/19-008r4/19-008r4.html	General - Geo	2019
GLOSIS	FAO & GSP	The GloSIS web ontology, developed by the Global Soil Partnership, enables standardized, semantic web-based access and integration of global soil data to support sustainable land management.	GloSIS: The Global Soil Information System Web Ontology | www.semantic-web-journal.net	Agriculture - Soil	2022
ICAR	ICAR	ICAR is the global authority providing independent Guidelines, Standards, and Certification to promote the development and improvement of animal identification, performance recording, and evaluation in farm animal production.	https://wiki.icar.org/index.php/Guidelines	Agriculture - Livestock	2024
INSPIRE	EU	The INSPIRE Directive establishes a European Spatial Data Infrastructure to support environmental policies by enabling the sharing and public access of spatial data across EU member states.	https://knowledge-base.inspire.ec.europa.eu/index_en	General - Geo	2025
IoT-LITE	W3C	Lightweight ontology for representing resources, entities and services within the Internet of Things (IoT) context.	IoT-Lite Ontology (w3.org)	Sensor IoT	2015
ISO 11783 (ISOBUS)	ISO	Tractors and machinery for agriculture and forestry—Serial control and communications data network	https://www.iso.org/standard/57556.html	Agriculture	2017
ISO TC 347	ISO	The Technical Committee 347 is titled Data-Driven Agrifood Systems and aims to improve the interoperability of agriculture and food systems by standardising data.	https://www.iso.org/committee/9983782.html	Agriculture	Under development
OGC Reference Model (ORM)	OGC	The OGC Reference Model provides a structured framework guiding the ongoing efforts of the Open Geospatial Consortium (OGC) in developing specifications and implementing interoperable solutions for geospatial data, services, and applications.	OGC Reference Model	General - Geo	2011

Standard	Organisation	Description	Link	Domain	Latest version
OMS (observations, measurements and sample)	OGC	The OMS standard (ISO 19156:2023) defines a conceptual model for describing observations, sampling, and their results to enable consistent data exchange across scientific and technical domains.	Observations, Measurements, and Samples - Open Geospatial Consortium (ogc.org)	General	2023
PCSM	TNO	The Pluotos Common Semantic Model (PCSM) aims data driven interoperability for the agri-food sector	https://ontology.tno.nl/ploutos/ploutos.ttl	Agriculture	2024
rmAgro	WUR	The referencemodel Agro provides a standardised framework for agricultural production data, enabling data integration and system interoperability across vairous agricultural systems and platforms.	https://rmagro.org/	Agriculture	2025
SAREF (4 AGRI, HEALTH)	ETSI	The SAREF4AGRI is an ontology extending SAREF to support interoperability in the Smart Agriculture and Food Chain domain by linking it with existing standards and ontologies.	https://saref.etsi.org/saref4agri/v2.1.1/	Agriculture	2020
SensorML	OGC	This standard defines a semantically rich framework for describing measurement processes, including sensors, actuators, and data transformations before and after measurement.	https://www.ogc.org/standards/sensorml/	IoT	2020
SKOS	W3C	The Simple Knowledge Organization System (SKOS) is a standardised data model designed to facilitate the sharing and linking of knowledge organisation systems on the Semantic Web.	SKOS	General	2009
SSN	OGC	The Semantic Sensor Network (SSN) is an ontology for describing observations and their properties for sensors and actuators.	Semantic Sensor Network Ontology (w3.org)	IoT	2017
WaterML	OGC	WaterML 2.0 is an interoperable standard for exchanging water observation data across systems, based on harmonised international models and existing OGC standards.	https://www.ogc.org/standards/waterml/	Agriculture - Water	2014

References

Crémer, J., de Montjoye, Y.-A., & Schweitzer, H. (2019). *Competition policy for the digital era*. European Commission. https://ec.europa.eu/competition/publications/reports/kd0419345enn.pdf

European Commission. (2017). *New European Interoperability Framework: Promoting seamless services and data flows for European public administrations*. Luxembourg: Publications Office of the European Union. https://ec.europa.eu/isa2/sites/default/files/eif_brochure_final.pdf

Thanos, C. "Mediation: the technological foundation of modern science" (2014) 13 Data Science Journal 88, 93.

Wegner, P. "Interoperability" (1996) 28 ACM Computing Surveys 285