Standardization Challenges in Precision Agriculture: Mapping the Landscape and Advancing Semantic Interoperability

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Abstract.

Background: Precision agriculture increasingly relies on digital technologies and the exchange of data between equipment, sensors, platforms, and decision support tools. Numerous standards exist to support interoperability, ranging from machine communication standards to semantic resources and data models. However, the overall landscape remains fragmented, and standards are often difficult to identify, compare, and apply in practice. Existing overviews provide useful snapshots but quickly become outdated due to the dynamic nature of standardisation efforts. There is therefore a need for approaches that support ongoing organisation, categorisation, and discovery of standards relevant to data exchange within the agricultural sector.

Methods: A qualitative and design-oriented approach was adopted, building on an existing catalogue of agricultural data standards. The initial dataset was reviewed and refined to include only standards with a clear agricultural focus. The dataset was subsequently extended through targeted searches across technical documentation, project deliverables, white papers, expert knowledge, and generative AI–assisted discovery. An inductive process was applied to derive a flexible categorisation framework consisting of six non-exclusive standard types: ontology or semantic model, controlled vocabulary or code list, information model, identifier scheme, exchange protocol, and guideline or best practice. Standards were also linked to one or more agricultural domains. The resulting dataset was implemented in a publicly accessible, community-based platform (agristandards.com), including browsing, filtering, and a constrained natural-language search interface.

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Results: The resulting platform provides a structured and extensible catalogue of agricultural standards, containing 30 standards linked to 21 organisations at the time of writing. This seed corpus is intended to demonstrate the categorisation framework and platform functionality rather than to represent the full standards landscape. Each standard is described using consistent metadata, including type, domain, and organisational context. The platform supports multiple modes of discovery, including filtering by type, domain, and organisation, as well as a retrieval-augmented search interface that answers user queries based solely on curated content. A community-based submission workflow was implemented to support future expansion. The platform demonstrates how heterogeneous standards can be organised in a consistent and accessible way without aiming for completeness.

Conclusion: This study demonstrates a practical approach for structuring and maintaining an overview of standards in digital agriculture through a community-based platform. By combining flexible categorisation, curated metadata, and user-oriented discovery mechanisms, the approach supports improved visibility and accessibility of standards in a fragmented landscape. The platform is positioned as a living overview that evolves over time. Future work will focus on expanding the catalogue, strengthening community engagement, and evaluating platform use in practice.

Keywords.
Standards, interoperability, semantics, information models, ISOBUS, retrieval-augmented generation

Introduction

Agriculture is undergoing a rapid process of digitalisation. An increasing number of digital applications, platforms, and data-driven services are being introduced across the agricultural sector, ranging from field-level decision support tools to farm management systems and machine-to-machine communication solutions. While this digital transition offers significant opportunities for improving productivity, sustainability, and resilience, it also introduces substantial challenges related to data exchange and interoperability (Roussaki et al., 2023; Wolfert et al., 2017). As digital solutions continue to emerge, the lack of shared standards hampers seamless integration between systems, devices, and organisations. thus limiting the full realisation of digital agriculture (Khatoon & Ahmed, 2022). This challenge is directly relevant to ongoing European efforts such as the HASHTAG project, which addresses machine data flows and authenticated interoperability across precision agriculture systems using ISOBUS/ISOXML, the Agricultural Electronics Foundation (AEF) Public Key Infrastructure (PKI), and Galileo OSNMA/HAS services (Hashtag, n.d.).

To address interoperability challenges, a wide range of standards has emerged at different levels and for different purposes. Some of these standards have reached a high level of maturity and adoption and can be considered common goods within the sector. A prominent example is the ISOBUS standard based on ISO 11783, which enables standardised communication between tractors and implements and has been widely adopted by machinery manufacturers (AEF, n.d.). In contrast, many other standards remain primarily within the research or innovation domain and have not yet achieved broad uptake by industry. This is particularly visible for semantic standards, such as ontologies and shared vocabularies, which aim to ensure that data is not only exchanged but also interpreted consistently across systems (Khatoon & Ahmed, 2022).

Standardisation efforts in agriculture are driven by multiple organisations operating at different levels. Generic international standardisation bodies such as the International Organization for Standardisation (ISO) and the International Electrotechnical Commission (IEC) develop formal standards through structured, member-based processes. In parallel, more agriculture-specific organisations play a crucial role in shaping digital standards tailored to sectoral needs. Examples include AgGateway, which focuses on data exchange standards for agricultural production systems, and the AEF, which coordinates compatibility and certification related to ISOBUS (AgGateway, n.d.; Agricultural Industry Electronics Foundation, n.d.). These organisations operate alongside research-driven initiatives and publicly funded projects, resulting in a complex and fragmented standards landscape.

Previous work has attempted to provide structured overviews of this landscape. A recent and relevant contribution is the technical paper by Atik and Urdu, developed within the XGain project, which identified and analysed a broad set of data standards relevant to interoperability in digital agriculture (Atik & Urdu, 2025). Their work provides a valuable snapshot of the state of standards as of mid-2025, with a strong emphasis on policy alignment, semantic interoperability, and gaps between regulatory ambition and sectoral practice. However, the standards landscape is inherently dynamic. New standards continuously emerge, existing standards evolve, and others become obsolete or are superseded. As a result, any static inventory of standards risks becoming outdated shortly after publication (Roccatello et al., 2025).

In addition, standards differ not only in maturity and adoption but also in scope, type, and domain. From a domain perspective, standards in digital agriculture cover a wide range of application areas, including arable farming, horticulture, livestock, machinery, supply chain processes, and cross-sector or cross-domain interactions (Atik & Urdu, 2025). From a functional perspective, standards can be of several types. For example, ontologies and semantic models aim to harmonise meaning and support semantic interoperability while controlled vocabularies and code lists ensure consistent representation of entities such as crops, activities, or identifiers. Other standards are structured as information models that define structured representations of agricultural data, while identifier schemes provide persistent and unambiguous references to entities. A single standard may fulfil multiple roles and may be applicable across multiple domains. Despite this diversity, clear and consistently applied categorisations across the agricultural standards landscape remain lacking.

Against this background, there is a need for an up-to-date, structured, and community-maintained overview of standards for digital agriculture. A comprehensive and complete list of standards is, by definition, unattainable, as the landscape continuously evolves. Instead, there is a need for an approach that supports ongoing identification, categorisation, and curation of standards, while making them easily findable and interpretable by researchers, practitioners, and developers.

This study aimed to address this need by combining a structured categorisation of digital agriculture standards with the development of a community-based platform that supports continuous updating and discovery of standards. Building on the work of Atik & Urdu (2025), the following research questions were addressed:

1. How can standards for digital agriculture be categorised in a clear and practically meaningful way?
2. How can digital standards relevant to agriculture be further identified and updated beyond existing overviews?
3. How can these standards be brought together in a platform that facilitates ongoing curation and updating?
4. How can standards for digital agriculture be made easily findable for different user groups?

By addressing these questions, this paper contributes to the structuring of the agricultural standards landscape and proposes an initial, living overview that can evolve over time.

Methods

This study adopted a qualitative and design-oriented research approach, combining desk research, expert knowledge, and iterative platform development. The methodological starting point was the standards overview developed by Atik and Urdu within the XGain project (Atik & Urdu, 2025). Their inventory of agricultural data standards served as the initial seed dataset for this study, providing a structured but necessarily incomplete snapshot of the standards landscape as of mid-2025.

First, the standards identified by Atik and Urdu were systematically reviewed against the following inclusion criteria: (i) explicit agricultural relevance, defined as a standard developed for or primarily applied within agricultural production, supply chains, or related advisory services; (ii) public availability of specifications or technical documentation; and (iii) evidence of active maintenance or recent application. During this review, standards not meeting these criteria were excluded. This included, for example, standards related primarily to water quality or general geospatial specifications originating from organisations such as the Open Geospatial Consortium (OGC). The remaining standards were analysed in terms of their scope, responsible organisations, domain coverage, and technical characteristics producing a refined initial corpus. This process resulted in a refined initial corpus of standards that formed the basis for further extension.

Second, the initial list was extended through a targeted search process and the application of expert knowledge. This process was not limited to formal academic literature but also included technical documentation, white papers, project deliverables, and exploratory searches using general web sources and generative AI–assisted discovery using Copilot. Relevant sources were examined to identify additional standards that were not included in the original overview. This step acknowledged that standards are not always described in peer-reviewed literature and that knowledge of emerging initiatives is often distributed across grey literature and practitioner communities.

Third, a data synthesis step was conducted to derive a clear categorisation of standards. Rather than relying on existing classifications from individual organisations, an inductive approach was applied to identify recurring functional roles across standards. As a result, six non-mutually exclusive standard types were defined: ontology or semantic model, controlled vocabulary or code list, information model, identifier scheme, exchange protocol, and guideline or best practice. A single standard could be assigned to multiple types, reflecting the hybrid nature of many contemporary standards.

In parallel, standards were associated with one or more agricultural domains. The domains considered in this study included arable farming, horticulture, livestock, machinery, supply chain processes, and cross-sector or cross-domain applications. Standards were allowed to be linked to multiple domains where applicable. Domain and type classification were treated as complementary dimensions for structuring the dataset.

Based on these classifications, a data model was defined specifying the metadata collected for each standard. This metadata included the standard name, responsible organisation, domain coverage, standard type(s), version or last update, and both short and extended textual descriptions. This conceptual data model guided both data entry and platform implementation. The corresponding entity–relationship structure is shown in Figure 1.

The curated dataset was implemented in a publicly accessible website, agristandards.com, which was developed as a community-based catalogue for digital agriculture standards (Agristandards.com, n.d.). The platform was created using a rapid prototyping approach, in which on-paper mock-ups were translated into system functionality through prompt-based development using the Lovable platform (Lovable, n.d.). The website was populated with the refined dataset and designed to support further extension over time.

To facilitate discovery, a lightweight retrieval-augmented generation (RAG) component was implemented as an auxiliary search interface over the curated standards catalogue (Gao et al., 2023). Standard descriptions and metadata were embedded and stored in a vector index, with retrieval restricted to the curated platform content; the generative step uses a general-purpose LLM constrained to summarising retrieved entries. Responses are returned only when relevant content is retrieved and are linked directly to the corresponding standard entries, ensuring traceability and avoiding speculative or unsupported outputs. This component was intentionally scoped as a supportive feature rather than a core methodological contribution. The language model is restricted to the contents of the standards database and only returns answers when relevant information is explicitly present. In such cases, responses are linked directly to the corresponding standard entries in the platform, thereby ensuring traceability and avoiding speculative or unsupported outputs.

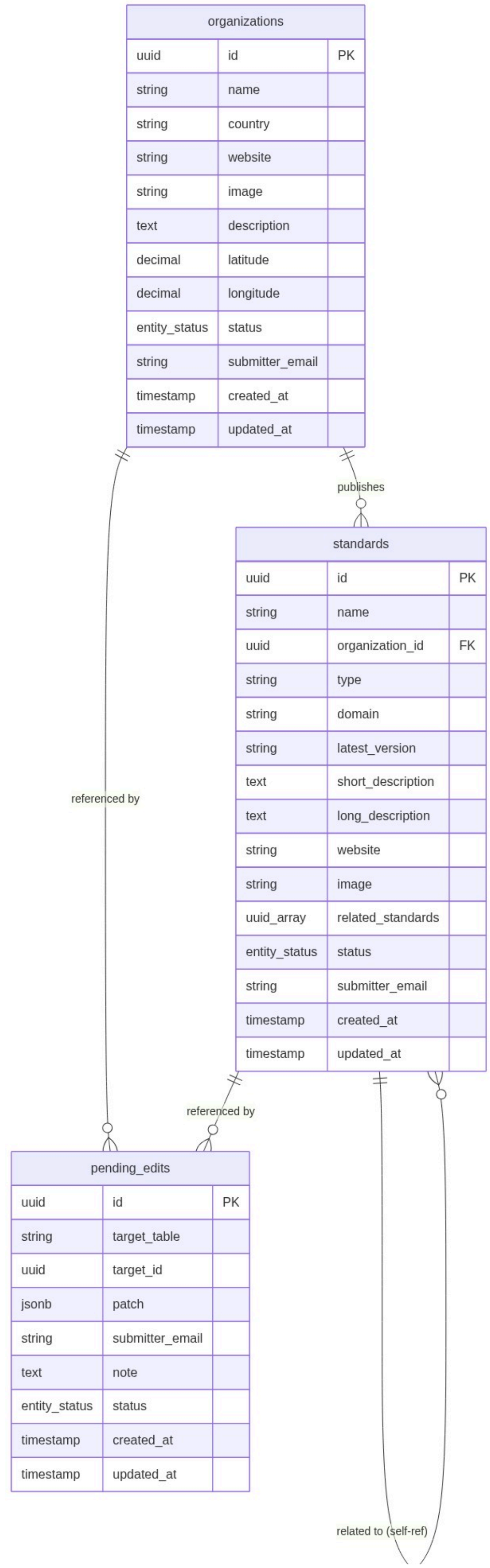


Figure 1: Entity Relationship (ER) diagram used for agristandards.com

Community-based curation was embedded as a core principle of the platform. Users can suggest new standards or propose updates via a structured submission form. All submissions are reviewed manually, with acceptance based primarily on relevance to digital agriculture and clarity of the provided information. This approach was chosen to maintain a balance between openness and basic quality control while enabling future growth of the catalogue.

Results

The main result of this study was the development of agristandards.com, a publicly accessible, community-oriented platform that brings together standards relevant to digitalisation within the agricultural domain (Agristandards.com, n.d.). At the time of writing, the platform contained 30 standards linked to 21 organisations involved in standardisation, research, or sectoral coordination. These standards are available in Table 1. All included standards relate explicitly to agricultural contexts and applications; no attempt was made to catalogue standards outside the agricultural domain. An overview of the platform homepage is shown in Figure 2.

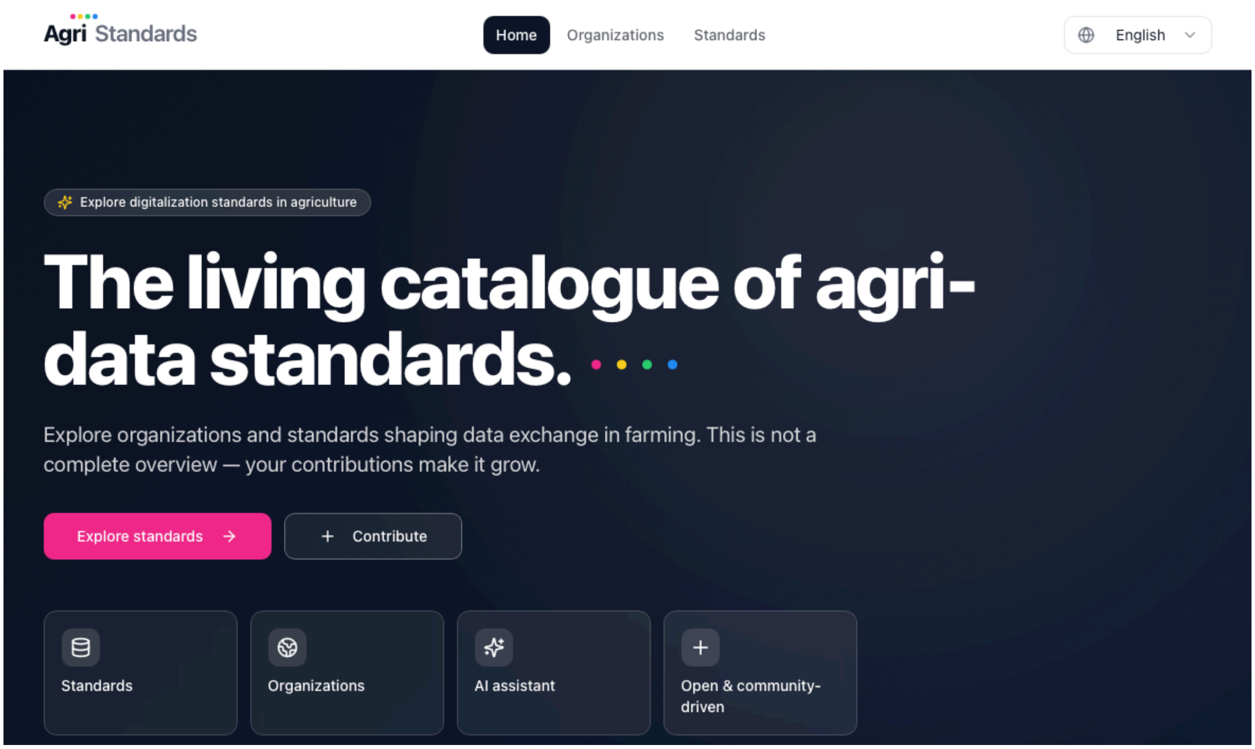


Figure 2: Screenshot of homepage of agristandards.com

Rather than aiming for completeness or statistical representativeness, the initial content of the platform was intended as seed material demonstrating how standards can be documented, categorized, and made discoverable in a consistent manner. The seed corpus extends the inventory of Atik & Urdu (2025) by removing non-agricultural entries, adding standards identified through targeted search and expert knowledge, and applying the categorisation framework developed in this study (see Methods).

Each standard in the platform was described using a structured metadata model, including information on responsible organisation, applicable agricultural domain(s), standard type(s), version or last update, and both short and extended textual descriptions. Standards were categorised using the six non-exclusive types defined in this study: ontology or semantic model, controlled vocabulary or code list, information model, identifier scheme, exchange protocol, and guideline or best practice. In addition, standards were linked to one or more agricultural domains, including arable farming, horticulture, livestock, machinery, supply chain processes, and cross-sector applications. This allowed individual standards to be associated with multiple domains and multiple functional roles.

Table 1: ***overview of included standards and responsible organizations, snapshot of June 5th 2026***

Name	Type	Domain	Organization
ADAPT	information model	Arable farming; machinery	AgGateway
AgMES	ontology / semantic model	cross-sector	FAO
Agroconnect code lists	controlled vocabulary / code list	cross-sector	AgroConnect
AgroPortal Ontologies	ontology / semantic model	cross-sector	INRAE
agroxml	exchange protocol	Arable farming; machinery	KTBL
AIM	ontology / semantic model	cross-sector	OGC
Classification of livestock for the agricultural census	controlled vocabulary / code list	livestock	FAO
Classification of machinery and equipment for the agricultural census	controlled vocabulary / code list	Arable farming; machinery	FAO
eDairy	exchange protocol	livestock	AgroConnect
Edi-crop	exchange protocol	Arable farming	AgroConnect
EPCIS	exchange protocol	supply chain; cross-sector	GS1
ePigs	exchange protocol	livestock	AgroConnect
EPPO Codes	controlled vocabulary / code list	Arable farming	EPPO
FIWARE Smart Data Models Agrifood	information model	cross-sector	FIWARE Foundation
Fresh upstream	exchange protocol	horticulture	GS1
Frug I Com	exchange protocol	horticulture	GS1
FSM	ontology / semantic model	cross-sector	Farmtopia
GLN	identifier scheme	supply chain; cross-sector	GS1
GTIN	identifier scheme	supply chain; cross-sector	GS1
ICAR Guidelines	guideline / best practice	livestock	ICAR
Indicative crop classification for the agricultural census (ICC)	controlled vocabulary / code list	cross-sector	FAO
ISO 11783 (ISOBUS)	information model	Arable farming; machinery	ISO TC23 / SC19; AEF
ISO TC 347	information model	cross-sector	ISO TC347
ISO xml	exchange protocol	Arable farming; machinery	ISO TC23 / SC19
ISOBUS Task Controller	exchange protocol	Arable farming; machinery	AEF
PAIL	information model	Arable farming; machinery	AgGateway
PLU Code	controlled vocabulary / code list	horticulture	IFPS
rmAgro	information model	cross-sector	WUR
SPADE	information model	Arable farming; machinery	AgGateway Europe
Tractor Implement Management (TIM)	exchange protocol	Arable farming; machinery	AEF (Agricultural Industry Electronics Foundation)

The platform provided multiple ways to explore the catalogue. Standards could be browsed directly or filtered based on standard type, agricultural domain, or responsible organisation. An overview of organisations included in the platform is shown in Figure 3. Selecting an organisation provides access to the associated standards, as illustrated in Figure 4 for the case of AgGateway. A detailed view of an individual standard, including its metadata and description, is shown in Figure 5 for the ADAPT standard.

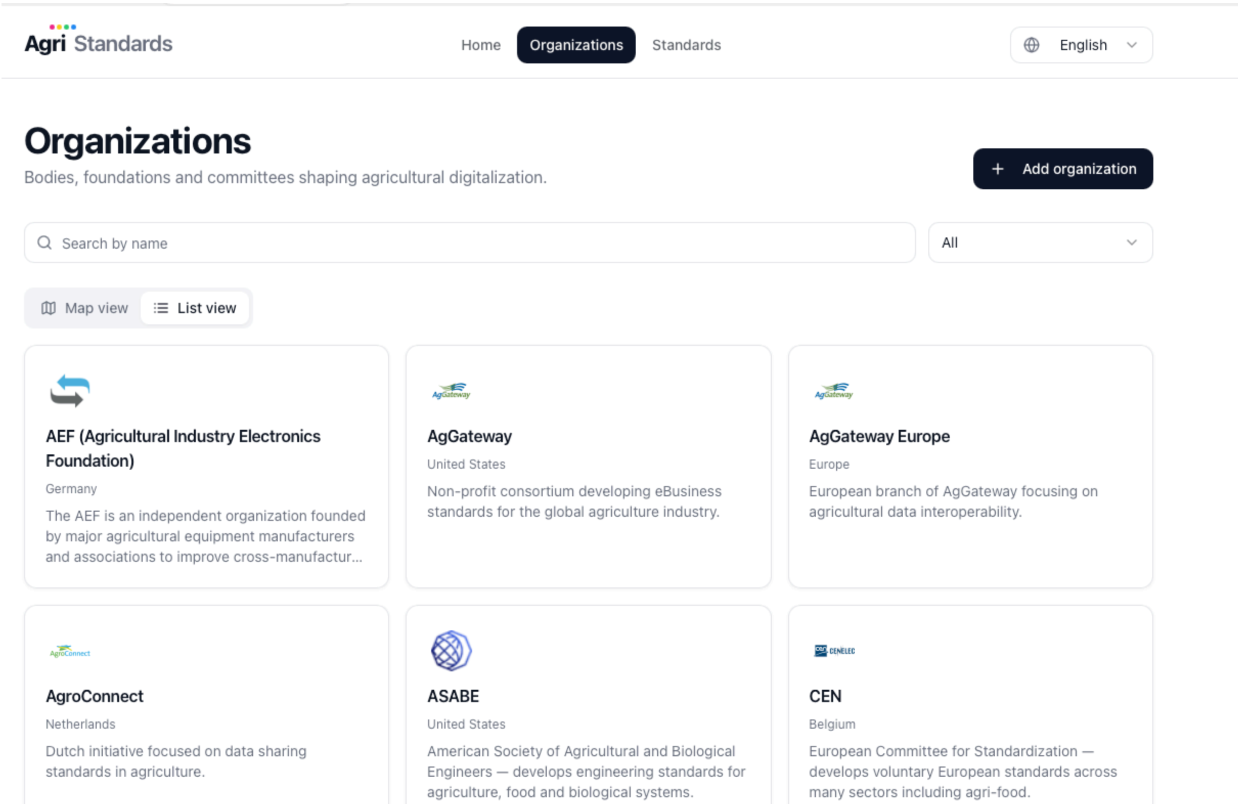
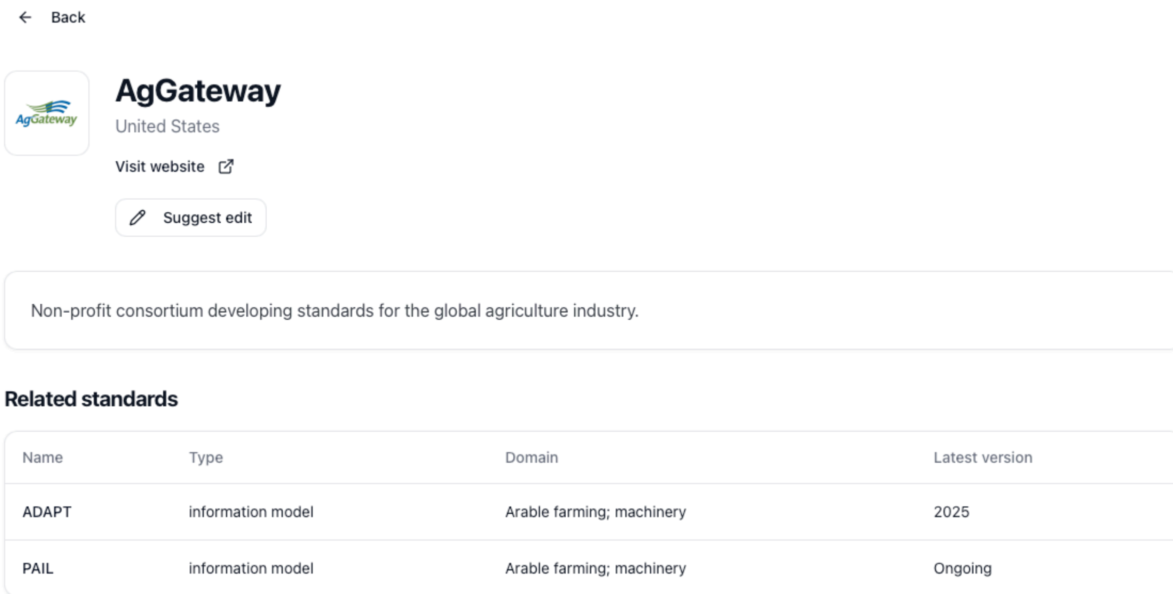


Figure 3: Screenshot of page with organizations active in standardization of digital agriculture



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AgGateway

United States

Visit website

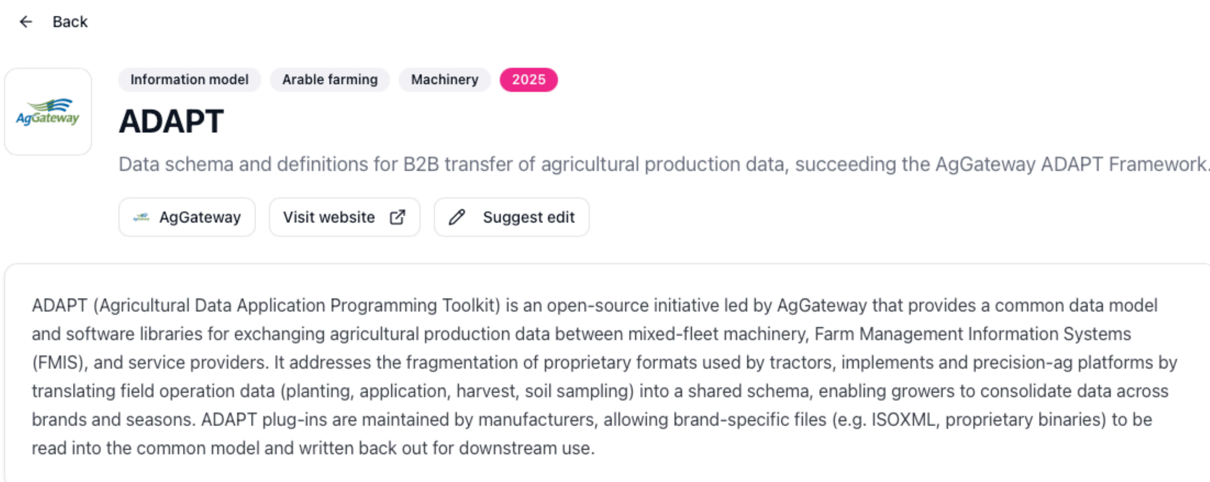
Suggest edit

Non-profit consortium developing standards for the global agriculture industry.

Related standards

Name	Type	Domain	Latest version
ADAPT	information model	Arable farming; machinery	2025
PAIL	information model	Arable farming; machinery	Ongoing

Figure 4: Screenshot of organization page of AgGateway



Back

Information model | Arable farming | Machinery | 2025

ADAPT

Data schema and definitions for B2B transfer of agricultural production data, succeeding the AgGateway ADAPT Framework.

AgGateway | Visit website | Suggest edit

ADAPT (Agricultural Data Application Programming Toolkit) is an open-source initiative led by AgGateway that provides a common data model and software libraries for exchanging agricultural production data between mixed-fleet machinery, Farm Management Information Systems (FMIS), and service providers. It addresses the fragmentation of proprietary formats used by tractors, implements and precision-ag platforms by translating field operation data (planting, application, harvest, soil sampling) into a shared schema, enabling growers to consolidate data across brands and seasons. ADAPT plug-ins are maintained by manufacturers, allowing brand-specific files (e.g. ISOXML, proprietary binaries) to be read into the common model and written back out for downstream use.

Figure 5: Screenshot of an individual standard

To further support discoverability, a lightweight retrieval-augmented generation (RAG) interface was implemented as an auxiliary feature. This interface allowed users to pose questions in natural language, after which relevant standards were retrieved from the database and summarised in a short textual response. An example of such a query, focusing on standards related to livestock, is shown in Figure 6. The RAG component was strictly constrained to the curated database contents and returned an answer only when relevant information was explicitly available. No external data sources were queried, and no inferential or speculative responses were generated. Responses were linked directly to the corresponding standard entries, ensuring traceability.

In addition to search and browsing functionality, the platform included a community-based submission workflow. Users were able to propose new standards or suggest updates to existing entries via a structured form. All submissions were reviewed manually. At the time of writing, moderation was carried out by a single reviewer, with acceptance criteria focused on relevance to digital agriculture and clarity of description. Although no external submissions had been processed yet, the workflow was fully operational and designed to support future community contributions.

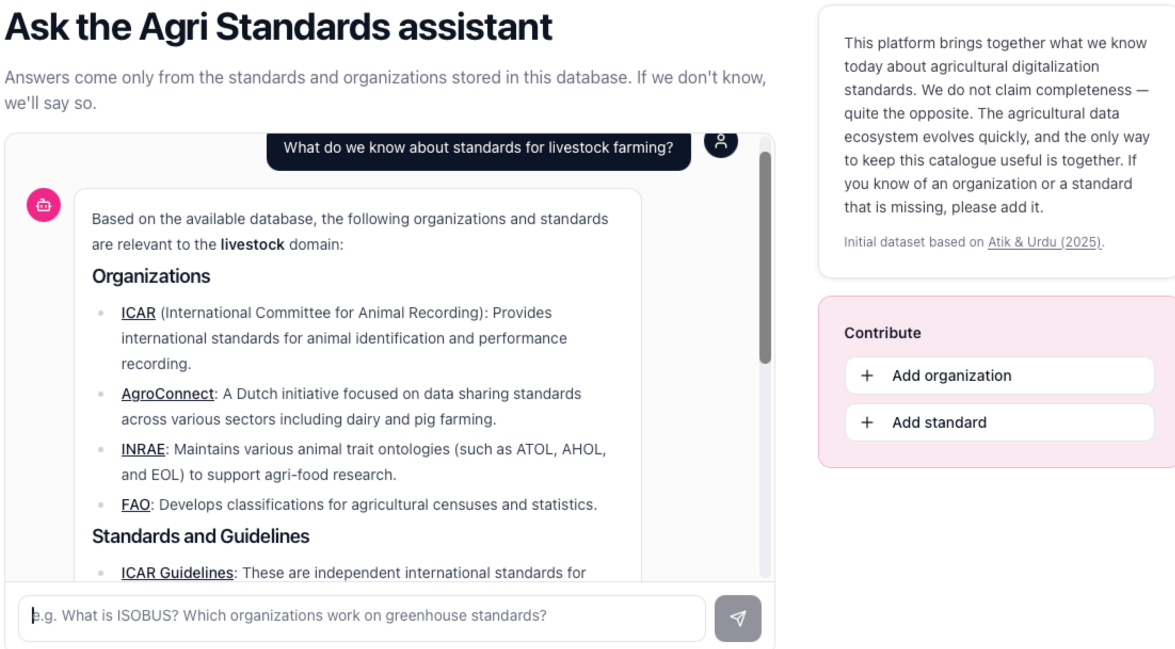


Figure 6: Screenshot of the RAG-based AI assistant for finding standards

Several existing initiatives address parts of the agricultural standards landscape, including AgroPortal for agricultural ontologies. Rather than duplicating these resources, agristandards.com is positioned as a complementary aggregator that spans multiple standard types (ontologies, vocabularies, information models, identifier schemes, exchange protocols, and guidelines) and provides a constrained natural-language search interface over its curated content. Specialised repositories such as AgroPortal are referenced as standards within the platform rather than replicated, allowing users to navigate from cross-type discovery into deeper domain-specific infrastructures

Discussion

This study addressed four research questions focused on the categorisation, identification, aggregation, and discoverability of standards for digital agriculture. Rather than producing a definitive or exhaustive inventory, the results demonstrated how a structured, community-oriented platform can support ongoing curation in a rapidly evolving standards landscape.

Regarding the first research question on how standards for digital agriculture can be categorised. The proposed typology of six non-exclusive standard types proved effective for structuring heterogeneous initiatives without forcing them into a single rigid classification. The categories: ontology or semantic model, controlled vocabulary or code list, information model, identifier scheme, exchange protocol, and guideline or best practice captured distinct functional roles while allowing overlap between types. Allowing standards to span multiple categories was found to better reflect their actual design and use, particularly where semantic definitions, data models, and exchange mechanisms are developed in parallel.

The second research question concerned the further identification of relevant standards. Building explicitly on the work of Atik & Urdu (2025) confirmed both the value and the limitations of static inventories. While their overview provided a strong foundation, extending it required interpretative decisions, expert judgement, and pragmatic inclusion criteria. This finding reinforces the central premise of this study: that maintaining an up-to-date overview of agricultural standards is less a one-time research task than an ongoing curatorial process.

The third research question focused on bringing standards together in a way that facilitates updating and maintenance. The results suggest that a lightweight, community-based platform with low barriers for contribution and manual moderation offers a viable approach, particularly in early stages. By prioritising accessibility and extensibility over formal completeness, the platform aligns with the notion of a living overview that evolves alongside the standards it documents.

The fourth research question addressed the findability of standards. The combination of conventional catalogue functionality with a constrained natural language interface illustrated how emerging AI-based tools can support exploration without compromising reliability. By deliberately limiting the RAG component to database content only, the platform avoided common risks associated with generative systems, such as hallucination or undocumented claims, while still lowering the threshold for engagement by non-expert users.

Several limitations should be acknowledged. The current version of the platform reflects the perspectives, expertise, and selection choices underlying the curation process and does not claim to represent the full agricultural standards ecosystem. In addition, a persistent challenge relates to the appropriate level of granularity. For example, certain organisations, such as the American Society of Agricultural and Biological Engineers (ASABE), publish large collections of standards (ASABE, n.d.). Including all individual standards would reduce usability and increase maintenance complexity. Therefore, a selective approach was applied, focusing on standards that are widely used or broadly applicable. This introduces an inherent trade-off between completeness and user friendliness.

A second limitation concerns the scope of the platform. The catalogue was intentionally restricted to standards with a clear and explicit agricultural focus. As a result, more generic standards, such as geospatial standards developed by organisations like the Open Geospatial Consortium (OGC), were not included, even though they are frequently applied within agricultural contexts. This scoping decision was made to maintain clarity and focus but may limit visibility of cross-domain dependencies.

Furthermore, no usage analytics or community engagement data were available at the time of writing, and governance arrangements beyond the initial moderation setup remain to be established. Consequently, evaluation of platform uptake, impact, and long-term sustainability was beyond the scope of this study.

To our knowledge, this study represents one of the first efforts to combine a structured categorisation framework with an operational, publicly accessible, community curated platform for documenting standards in digital agriculture. It should therefore be interpreted as an initial contribution rather than a final solution. Future work should focus on expanding community participation, refining governance mechanisms, and empirically assessing how different stakeholder groups interact with and benefit from such a platform.

Conclusion

This paper presented an initial contribution toward structuring and maintaining an overview of standards for digital agriculture through the development of a community-based platform. Building on earlier work by Atik & Urdu, (2025), a flexible categorisation framework was defined and operationalised within a publicly accessible catalogue. Rather than aiming for completeness, the platform was positioned as a living overview that supports continuous curation in a dynamic and evolving standards landscape. By combining structured metadata, community-based submissions, and a constrained natural-language search interface, the approach demonstrated how standards can be made more discoverable while maintaining reliability.

Although the current implementation represents a first, seeded version with limited coverage and evolving governance, it provides a practical foundation for supporting interoperability in digital agriculture. Future work will focus on expanding community participation, refining governance mechanisms, and evaluating usage and impact as the platform matures.

Acknowledgments

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AI Statement

The authors used generative artificial intelligence tools (Microsoft Copilot Enterprise) for language refinement, proofreading, and improving the clarity and readability of the manuscript.

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