



Deliverable D2.3

**Synthesis of opportunities for wider exploitation
and upscaling of data, technologies and R&I results
in livestock tracking**

digi4live.eu



Author(s)	Bartzanas, T., Arsenos, A. Vouraki, S., Anestis, V., Arsenos, G., Tolmačev, A.
Organisation(s)	AUA, FSH
Contributor(s)	Tolmačev, A., Bosnić, U
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Abstract:	One of the goals of Digi4Live is to advance the digital transformation of livestock systems through the structured use of data and technology. Deliverable 2.3 contributes to this goal by developing a unified analytical framework and methodology for assessing digital and data-driven innovations, along with stakeholder needs and grassroots-level practices in the livestock sector that have been examined during the first 18 months of the project. The framework was designed to integrate insights from digital tools, stakeholder feedback, and regulatory environments, and is structured around seven core dimensions: tool functionality, stakeholder alignment, usability and accessibility, data interoperability and standards, systemic barriers and enablers, impact potential, and scalability and replicability. Each dimension supports a structured, comparable, and context-sensitive analysis of innovation readiness and adoption potential across regions and production systems. To support the development of this methodology, an AI-assisted analytical approach was piloted using a fine-tuned Large Language Model (LLaMA 2). The model was trained on project-specific sources, including the digital tool inventory, regulatory texts, and stakeholder input, thus enabling semantic analysis and cross-referencing while ensuring transparency, ethical safeguards, and human oversight. The deliverable synthesizes evidence from previous work and identifies key strategic opportunities, systemic gaps, and persistent barriers to digital innovation in the sector. These include challenges related to data interoperability, legal complexity, and usability, as well as enablers such as standardization initiatives, modular design, multilingual support, and AI-driven guidance tools. The resulting methodology provides a practical basis for future co-creation, policy engagement, and digital tool development work, and lays the groundwork for responsible, evidence-based adoption of digital technologies across the European livestock sector.

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5.	INSTITUT NATIONAL DE RECHERCHE POUR L'AGRICULTURE, L'ALIMENTATION ET L'ENVIRONNEMENT	INRAE	France
6.	KATHOLIEKE UNIVERSITEIT LEUVEN	KUL	Belgium
7.	JOHANN HEINRICH VON THUENEN-INSTITUT, BUNDESFORSCHUNG INSTITUT FUER LAENDLICHE RAEUME, WALD UND FISCHEREI	Thuenen	Germany
8.	STICHTING WAGENINGEN RESEARCH	WR	Netherlands
9.	INSTYTUT GENETYKI I BIOTECHNOLOGII ZWIERZAT POLSKIEJ AKADEMII NAUK	IGBZ	Poland
10.	INSTITUT DE L'ELEVAGE	IDELE	France
11.	TEKNOLOGISK INSTITUT	DTI	Denmark
12.	INTERNATIONAL COMMITTEE FOR ANIMALRECORDING	ICAR	Netherlands
13.	AGDATAHUB	ADH	France
14.	RUOKAVIRASTO	FFA	Finland
15.	TEKNOLOGIAN TUTKIMUSKESKUS VTT OY	VTT	Finland
16.	WAGENINGEN UNIVERSITY	WU	Netherlands

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Table 1: List of abbreviations and acronyms.

List of Abbreviations and Acronyms	
AI	Artificial intelligence
ATP	Agricultural technology provider
CS	Case study
DPP	Digital product passport
EBV	Estimated breeding value
EU	European Union
GDPR	General Data Protection Regulation
GHG	Greenhouse gas emissions
GPS	Global positioning system
IoT	Internet of things
IPPC	International Plant Protection Convention (IPPC)
LCA	Life cycle assessment
LCI	Life Cycle Inventory
PEF	Product Environmental Footprint
PLF	Precision livestock farming
RFID	Radio frequency identification
TRACES	Trade Control and Expert System
WOAH	World Organization for Animal Health
WP	Work package

1. Introduction

The livestock sector across Europe is undergoing a digital transformation, and a growing demand for transparency, sustainability, animal welfare, and traceability. The Digi4Live project seeks to harness the power of digital and data-driven solutions to meet these demands by building a coordinated, evidence-based, and user-centered approach to livestock tracking. In this context, Deliverable 2.3 (D2.3) reports results of task T2.4 of Digi4Live, and serves as a synthesis of the findings from Work Package 2 (WP2), focusing on the inventory of digital tools and datasets (T2.1), identification of user needs and barriers (T2.2), and analysis of the regulatory and policy landscape (T2.3).

The aim of this deliverable is to identify and communicate concrete opportunities for scaling and expanding the use of digital technologies, livestock tracking data, and research and innovation (R&I) results. This is done by:

- Mapping how existing tools and datasets can be repurposed or enhanced for broader use,
- Highlighting scalable solutions and viable cross-regional applications such as cloud-based platforms for herd management and traceability, smart milking systems, wearable sensors for real-time health and fertility monitoring and precision feeding technologies and AI-assisted decision support systems,
- Synthesizing stakeholder perspectives and policy reviews to detect gaps and barriers to digital adoption,
- Recommending actionable strategies to support adoption of digital technologies through policy, design, and education.

Tasks T2.1, T2.2 and T2.3 already provided insights into the landscape of digital solutions, the experiences and needs of users, and the regulatory frameworks that shape adoption. However, in the absence of a unifying structure, these findings risk remaining valuable in parts, but fragmented. The purpose of T2.4, and hence this deliverable, is to bring these insights together into a structured and transparent approach for evaluating digital livestock solutions, their alignment with stakeholder needs, and their potential for scaling within a policy-compliant and socio-economically diverse Europe. Therefore, this deliverable introduces a common analytical framework, supported by a Large Language Model (LLM)-based artificial intelligence (AI) consultant. The AI-enhanced element was instrumental in synthesizing the diverse evidence streams outlined above, technological data, stakeholder insights, and regulatory texts into a coherent, multi-dimensional methodology. It enabled structured analysis and dynamic insight generation across complex and varied data sources, while maintaining human oversight, transparency, and ethical compliance. As such, the deliverable provides insights for practical action as well as evidence for how digital intelligence can support the responsible transformation of livestock tracking across Europe.

2. Overview of input data and their relevance

2.1. Inputs from the task concerning inventory of tools, datasets, stakeholder interviews and digital initiatives in livestock tracking

2.1.1. Scope and methodological approach

T2.1 of the Digi4Live project laid the groundwork for understanding the current landscape of digital solutions in the European livestock sector. Its core objective was to develop a structured and detailed inventory of existing digital tools, data sources, industrial applications, and research initiatives relevant to livestock tracking. While initially designed as a comprehensive catalogue of available resources, this inventory also provides a foundational input for the analytical work presented in this deliverable. It enables the classification of tools by maturity, usability, application domain, and potential for interoperability and scaling, contributing directly to the development of the common analytical framework.

To achieve these goals, the Digi4Live consortium conducted a systematic identification and characterization of digital solutions. The inventory was compiled using a shared digital platform, initially hosted on Vercel and based on a structured Google Sheets model, which allowed the classification and documentation of:

- Commercial products and industrial solutions (e.g., wearable sensors, GPS trackers),
- Digital applications (e.g., livestock management apps, animal ID platforms),
- Data sets and databases (e.g., traceability records, breeding data, environmental metrics),
- National and EU-funded projects (e.g., Horizon 2020, EIP-Agri initiatives).

Each entry was assessed and categorized by type, application area, species covered, user type, and additional metadata such as interoperability, maturity, and compliance with regulatory frameworks. This classification was supported by keyword indexing and web-based validation of content accuracy.

2.1.2. Strategic relevance for D2.3

The database included over 370 entries, reflecting a vibrant and growing ecosystem of digital tools and initiatives in the livestock domain. The inventory revealed asymmetries in species and application focus. Dairy cows were by far the most frequently addressed livestock sub-category, accounting for 72.9% of identified products, followed by pigs, beef cattle, and poultry. The dominant application domain was animal health and welfare, accounting for nearly 92.5% of the identified solutions. This suggests market and regulatory pressures around animal welfare, but also highlights underexploited areas such as emissions monitoring, breeding optimization, and environmental aspects.

For the present deliverable, the T2.1 inventory serves several foundational purposes. First, it provides a quantitative and qualitative basis for identifying which digital solutions are best suited for scaling, across regions, species, or production systems. Second, it enables cross-referencing of technical functionality with stakeholder feedback (from T2.2) and policy requirements (from T2.3), supporting a multi-dimensional evaluation of fit and feasibility. Third, it offers a structured dataset that can be analyzed and expanded through an LLM-based AI consultant, which is tasked with identifying latent patterns, mapping gaps, and proposing optimal matches between tools and user needs. Moreover, the findings of T2.1 directly inform the design of the common analytical framework proposed in D2.3. The variation in tool maturity, regulatory alignment, and functional scope across the entries illustrates the need for a standardized methodology to evaluate readiness and integration potential, which is a core goal of this deliverable.

2.2. Inputs from the task concerning gaps and barriers in livestock tracking

2.2.1. Scope and methodological approach

T2.2 of the Digi4Live project aimed to gather and analyze qualitative insights from key stakeholders involved in or affected by the deployment of digital technologies in the livestock sector. Unlike the tool-centric focus of T2.1, this task centered on understanding the human, institutional, and organizational factors that influence technology adoption, including user needs, operational challenges, perceived benefits, and systemic barriers. The input from T2.2 provides essential contextual depth for the present deliverable, as it links the technical capabilities catalogued in T2.1 with real-world expectations, constraints, and behaviors across Europe.

The core objective of T2.2 was to capture diverse stakeholder views across the livestock value chain. These stakeholders included farmers and livestock producers, technology developers and service providers, authorities, regulators, researchers and other academic experts, veterinarians and advisory service providers and representatives from industry and cooperative organizations.

To achieve a representative sample, the project conducted 52 key informant interviews across nine EU countries, corresponding to the locations of the six Digi4Live case studies. The interviews followed a semi-structured format and were supported by a detailed questionnaire developed by the consortium (Annex 1 of D2.1). These interviews covered a broad set of themes, including:

- Technology use and familiarity,
- User requirements and pain points,
- Maturity, planning and implementation strategy,
- Needs for standardization,
- Conformance and certification,
- Data sharing and legislation,
- Perceptions of costs, value, and effort, and
- Data and strategy.

In addition to the interviews, input was gathered from a co-creation webinar that brought together multiple stakeholder groups to validate preliminary findings and elaborate on challenges and enablers. Moreover, a literature review on key implementational gaps and barriers in livestock tracking and recommendations for increasing technology adoption was performed.

2.2.2. Strategic relevance for D2.3

The findings of T2.2 provide essential inputs for several core components of this deliverable. In particular, they inform the common framework's stakeholder assessment dimension, helping define criteria for digital readiness, literacy, trust, and economic feasibility. They also contribute directly to the LLM-based consultant's training data, allowing the AI to understand patterns in stakeholder behavior, sentiment, and context-specific barriers. In addition, they help identify targeted intervention strategies such as subsidies, co-design programs, or regulatory clarification that can support broader adoption and impact. They also validate the need for modular, adaptable solutions rather than one-size-fits-all approaches, reinforcing the importance of contextual relevance in digital scaling.

By linking digital tool availability (T2.1) with stakeholder demand and capacity (T2.2), this deliverable can formulate practical, user-driven recommendations for upscaling innovation in the livestock sector.

2.3. Inputs from the task concerning regulatory and policy landscape for data and digital technologies in livestock

2.3.1. Scope and methodological approach

T2.3 examined the regulatory and policy environment shaping the development, deployment, and adoption of digital technologies in the European livestock sector. Building on the technological inventory of T2.1 and the stakeholder insights from T2.2, this task provided a legal and institutional perspective that is essential for assessing the feasibility, constraints, and enablers of digital innovation at scale. T2.3 also served to identify where harmonization, clarification, or additional guidance is needed to bridge the gap between policy objectives and grassroots realities.

The primary aim of T2.3 was to review existing EU and national legislation, standards, and policies related to data governance, digital technologies, and livestock traceability. The task focused particularly on:

- Laws governing data protection, sharing, and access (e.g., GDPR, Data Act, Data Governance Act),
- Regulations related to digital product certification, interoperability, and standardization,
- Animal identification, health, and welfare legislation, especially where digital compliance is required,
- Upcoming EU frameworks such as the AI Act, which have direct implications for algorithmic tools used in farming.

This task also examined the soft regulatory landscape such as voluntary standards, codes of conduct (e.g., the EU Code of Conduct on Agricultural Data Sharing), and funding or policy programs that promote digital transition (e.g., CAP reform, Horizon Europe, Digital Europe Program). The task combined a desk-based policy review with partner contributions across Member States, ensuring both EU-level and national-level instruments were considered. This work included mapping relevant legislative texts and identifying overlaps or conflicts, assessing how these instruments impact the rights and obligations of different stakeholders (e.g., data controllers, processors, farmers, developers), identifying regulatory bottlenecks or ambiguities that hinder adoption or innovation, and finally evaluating the extent to which current frameworks support trust, transparency, interoperability and innovation.

2.3.2. Strategic relevance for D2.3

The findings from T2.3 are crucial for grounding the D2.3 analysis in legal and institutional reality, ensuring that recommendations are technically viable, compliant with regulations and aligned with policies. Digital agriculture increasingly operates at the intersection of data-related laws, animal welfare regulation, and policies concerning data and technology. The insights from T2.3 ensure that this deliverable offers practically grounded, policy-relevant, and ethically robust pathways for scaling up digital livestock solutions across Europe.

In particular, T2.3 informed this deliverable about the policy compliance and ethics layer of the common analytical framework. T2.3 also contributed to training the LLM-based consultant to recognize regulatory patterns and requirements, ensuring its output reflects legal constraints and opportunities. Moreover, T2.3 helped in identifying opportunities for regulatory improvement, including areas where clearer guidance, enhanced harmonization across EU member states, or the introduction of supportive policy instruments could facilitate the wider adoption and scaling of digital solutions. It also helped in enhancing stakeholder trust by aligning digital solutions with principles of data sovereignty, transparency, and accountability.

3. Towards a common framework for analysis and action

3.1. Objectives of the framework

This section outlines the purpose, design, and architecture of the framework, which serves as the foundation for the methodology proposed later in this document. It is a living structure rather than a static tool, adaptable to different contexts, user groups, and types of innovation, capable of supporting future assessments across case studies, regional pilots, and policy initiatives.

The development of a common analytical framework within Task 2.4 represents a pivotal step in translating the rich but diverse findings of WP2 into a coherent, actionable structure. Rather than being a conceptual abstraction, this framework is designed as a practical tool for evaluation, comparison, and decision support, intended to serve farmers, developers, policymakers, and researchers alike.

The framework responds to several needs identified throughout Tasks T2.1, T2.2, and T2.3: the fragmentation of digital tools across regions and species, the varying levels of stakeholder digital literacy and infrastructure, and the ambiguity surrounding regulatory compliance and data governance. The framework has been constructed around the following four objectives:

1. Systematize the insights of WP2 into a coherent evaluation model

Each task in WP2 has provided a vital perspective. While individually rich, these outputs needed a unifying logic to enable structured analysis. The framework integrates these dimensions—technological, social, and regulatory—into a single evaluation structure. It does not reduce their complexity but makes that complexity more understandable, manageable and comparable.

2. Provide a lens for understanding innovation readiness and contextual fit

The mere existence of a digital solution, such as those catalogued in the Digi4Live inventory, is not sufficient for it to be useful. It is critical to understand whether the solution is appropriate for its intended context and end users. This framework evaluates whether the tool can realistically be adopted by a specific user group (e.g., smallholder dairy farmers, regional veterinary authorities, technologically skilled large-scale producers) and whether it is compatible with the physical, economic, and regulatory environment of a particular region. By doing so, the framework enables context-aware evaluation, recognizing that digital innovation must be tailored to local conditions in order to be effective and scalable.

3. Support usability, scalability, and alignment with policy and business models

Digital tools do not exist in isolation. Their success depends on whether they are easy to use, cost-effective, and compliant with evolving EU legislation. The framework anticipates practical implementation challenges and supports the identification of tools that are both effective and deployable at scale by evaluating the following four aspects:

- Usability: Is the interface intuitive and accessible?
- Scalability: Can the solution be extended across species, farms, or countries?
- Legal and policy alignment: Does the tool comply with GDPR, the Data Act, the AI Act, and national livestock regulations?
- Business model viability: Is the tool financially sustainable for developers and affordable for users, especially in low-margin sectors?

4. Ground the analysis in real-world farming and innovation conditions

This framework was designed to reflect the realities faced by actors across the livestock sector, covering for example high-tech hubs and rural, low-connectivity, or resource-constrained settings. It acknowledges that digital transformation is uneven and must be approached inclusively. The framework takes into account

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limitations in broadband access, differences in technical support availability, regional disparities in public funding or digital infrastructure, and cultural preferences and trust dynamics in data governance.

To ensure that this framework remains technically robust, fair, and relevant, its design was guided by five key performance principles, which guided the evaluation:

- **Accuracy:** The framework must reflect actual capabilities and user experiences without distortion or oversimplification.
- **Reliability:** It must provide consistent evaluations across different technologies, actors, and use cases.
- **Scalability:** The structure must support assessments from local pilots to EU-level strategies.
- **Cost-efficiency:** Indicators must consider the financial implications of adoption for different stakeholders.
- **Usability:** Both the framework itself and the tools it assesses must be user-friendly and fit-for-purpose.

These principles serve as the evaluative backbone for both the assessment process and the solutions analyzed. They ensure that the framework is analytically rigorous and capable of informing funding priorities, innovation strategies, and policy reforms in a way that resonates with the needs and capacities of the livestock sector.

3.2. Framework dimensions

3.2.1. Structured criteria for analysis

To enable a comprehensive and consistent assessment of digital solutions in the livestock sector, the analytical framework is structured around seven core dimensions. These dimensions reflect the most critical factors influencing the relevance, usability, impact, and scalability of innovation, ensuring that tools are technically effective, practically deployable, economically viable, and socially acceptable. Each dimension captures a perspective that makes a digital solution successful or problematic. Together, they support a holistic and flexible evaluation process, adaptable to different actors, regions, and policy goals.

1. Solution mapping

This dimension provides a clear understanding of what a digital tool or dataset is designed to do. It categorizes solutions according to their primary functionality, such as monitoring animal health, recording movement, enabling traceability, or assessing environmental impact. It also evaluates the Technology Readiness Level (TRL) to determine whether the solution is still in development, ready for deployment, or already in widespread use.

Part of this dimension assesses integration capability, how well the tool can plug into existing digital infrastructures, such as farm management software, national databases, or certification systems. Solutions that are modular, compatible, and use open data formats tend to be well-positioned for uptake.

2. Stakeholder needs and readiness

This dimension evaluates how well a tool aligns with the priorities, constraints, and capabilities of its intended users. Stakeholders, including farmers, veterinarians, authorities, technology providers, consumers, and researchers, are diverse and have their own goals and expectations. By foregrounding the human element, this dimension helps avoid the common mismatch between technical potential and practical usability.

The key criteria include:

- **Perceived value:** Does the tool solve a relevant problem?
- **Usability preferences:** Are interfaces accessible? Are instructions clear? Is support available?
- **Readiness and capacity:** Do users have the necessary digital infrastructure, skills, and willingness to adopt the technology?

3. Usability and accessibility

Even a powerful tool can fail if it is too difficult or expensive to use. This dimension focuses on the design and delivery of the user experience:

- User Interface (UI): Is it intuitive, mobile-responsive, and available in multiple languages?
- Support and training: Are there tutorials, helplines, or peer networks that can help users learn and troubleshoot?
- Affordability: What is the pricing model free, subscription, pay-per-use, or publicly subsidized?

These factors are especially important in determining whether solutions are inclusive and usable especially by smallholders, cooperatives, and regions with limited resources.

4. Data and interoperability

The value of data depends on how easily it can be shared, integrated, and protected. Solutions that promote data portability, adhere to clear consent protocols, and support system-level integration are more likely to scale and deliver long-term value. This dimension assesses:

- Types of data collected: e.g., animal ID, health, environmental metrics, production statistics.
- Standards compliance: Does the tool align with ICAR, ISO, or EU codes for data sharing in agriculture?
- Data sharing mechanisms: Are APIs available? Is data exchange secure and compliant with the GDPR?

5. Barriers and enablers

Many promising tools fail to achieve the uptake because of external constraints. This dimension identifies both obstacles and influencing adoption. This dual perspective helps in designing actionable strategies to either remove or mitigate key bottlenecks. The key aspects include:

- Technical barriers: Limited rural internet, lack of hardware compatibility, sensor accuracy issues.
- Regulatory challenges: Ambiguity around data ownership, high compliance costs, unclear AI risk classification.
- Economic and social inhibitors: Lack of trust, insufficient training, absence of incentives or funding.

This dimension also captures enablers such as regional innovation programs, supportive policy environments, knowledge-sharing networks, and co-creation platforms that bring users and developers together.

6. Impact dimensions

Beyond functionality, digital solutions should be evaluated based on the positive change they create. Impacts are particularly relevant for aligning technological innovation with EU policy priorities such as the Green Deal, Farm to Fork, and Common Agricultural Policy objectives. This dimension considers four areas of impact:

- Animal Welfare: Does the tool enable earlier detection of health issues or improve living conditions?
- Environmental Sustainability: Can it help track emissions, optimize resource use, or support compliance with environmental goals?
- Profitability and Productivity: Does it reduce costs, improve yields, or streamline operations?
- Administrative Efficiency: Can it reduce paperwork, improve record-keeping, or ease regulatory reporting?

7. Scalability and replicability

Digital solutions must work across regions, species, and production models. This dimension helps identify which innovations are strategically scalable, and ready for both isolated use and widespread uptake. This dimension assesses:

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- Use-case flexibility: Can a tool designed for dairy cows also be used for pigs, poultry, or sheep?
- Regional fit: Is the tool adaptable to different regulatory systems, climatic zones, and languages?
- Business model robustness: Is the tool viable over time? Can it serve both public and private sector users? Does it provide clear benefits to all actors in the value chain?

To develop and apply this framework across a large, multilingual, and complex dataset, the authors relied on the analytical assistance of an LLM-based AI consultant. This digital assistant, described in the next section, supported semantic classification, synthesis of interview data, and policy mapping, helping ensure the framework was grounded in both evidence and context.

3.2.2. A scalable, responsible AI-augmented approach

The complexity, scale, and heterogeneity of materials originating from tasks T2.1, T2.2 and T2.3 presented an analytical challenge. Carrying out an integrated analysis manually, while indispensable for contextual understanding and interpretive depth, was challenging for several reasons. First, the volume of data, including narrative texts, structured inventories, and policy documents, exceeded what could reasonably be processed with consistency using traditional qualitative coding or spreadsheet-based comparison. Second, the material was varied in format and focus, requiring a system capable of connecting insights across sectors, geographies, and regulatory layers.

To meet this need, the authors employed a Large Language Model (LLM)-based AI assistant as an internal support tool. The goal was not to automate decision-making, but to augment human analysis, helping structure unstructured data, detect patterns, and cross-reference stakeholder feedback with technical and legal references. The LLM offered the capacity to process and organize large volumes of input without sacrificing consistency or granularity (i.e. scalability). In addition, it offered the ability to detect connections across domains (i.e. semantic insight). For example, linking stakeholders' concerns to relevant regulatory provisions or matching functional needs to tool capabilities. The LLM was flexible to handle diverse input, regional diversity, and cross-species considerations (i.e. context sensitivity).

The use of this AI tool was designed to respect the principles of responsible, human-centered analysis. All outputs were subject to expert validation, and no conclusions were generated without human interpretation and contextual judgment. Ethical safeguards, including documentation of sources, "explainability" of outputs, and bias monitoring were in place throughout the process. The use of the LLM was instrumental in enabling the authors to construct a framework and methodology that is both scalable and grounded, capable of reflecting the full diversity of European livestock systems. The next section explains how this tool was integrated into the evaluation process, the controls that were established to ensure transparency and trustworthiness, and the value it added to the overall analytical approach.

3.3. Integration of an LLM-based consultant in analysis

3.3.1. Purpose and role of LLM

The integration of a Large Language Model (LLM)-based consultant into the Digi4Live analytical process was driven by the need to interpret and synthesize a vast, heterogeneous, and interdependent body of information collected through WP2. This required synthesizing evidence from three datasets: **i)** a structured inventory of 370+ tools and datasets, each with metadata and descriptions (from T2.1), **ii)** 52 open-ended key-informant interviews and input from workshop discussions, rich in context (T2.2), and **iii)** A layered analysis of EU regulatory frameworks governing digital adoption and data sharing (T2.3). These dataset varied not only in format (structured, semi-structured, unstructured), scale and domain.

The LLM-based on the open-source LLaMA 2 architecture was a ready-to-use solution that was adapted to project-specific needs through targeted fine-tuning on relevant datasets (including the inventory, regulatory

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texts, and stakeholder feedback). This ensured that the outputs were context-aware and aligned with the analytical goals of the framework.

The LLM was used as a semantic reasoning assistant. The LLM was not used to generate findings independently, nor was it integrated into the final deliverable as a software product. Instead, enabled the research team to navigate complex inputs, identify thematic connections, and ensure consistency across layers of evidence, all while maintaining transparency, and expert oversight. It supported the authors in several key roles:

- **Knowledge structuring:** The LLM helped organize and link elements across data sources. For example, it could group tools from the inventory by their readiness for smallholder contexts or extract stakeholder perceptions about data privacy across countries. These outputs helped populate the framework's dimensions (e.g., usability, interoperability, regulatory fit) with relevant evidence.
- **Semantic alignment:** A central challenge in WP2 was connecting stakeholder narratives (e.g., a farmer's concern about surveillance) with abstract legal frameworks (e.g., GDPR provisions on personal data processing). The LLM could recognize and map these cross-domain relationships, helping us align perceptions with policy and functionality with user need.
- **Pattern detection:** By classifying and clustering similar themes across interviews or tool descriptions, the LLM supported the identification of recurring needs, pain points, or enabling factors.
- **Acceleration and consistency:** The LLM enabled faster synthesis of large document sets, maintaining a uniform interpretive logic across regions, languages, and sectors. This reduced the manual burden while enhancing the traceability and consistency of comparisons.
- **Contextual flexibility:** Through domain-specific tuning, the LLM helped ensure that the evaluation reflected the specificity of regional conditions, production systems, and user groups. For instance, it could adapt its interpretation of "usability" based on whether the user was a goat herder in southern Spain or a poultry cooperative in northern Germany.

Unlike traditional keyword search or rule-based systems, the LLM offered the capacity for semantic reasoning, understanding meaning rather than just matching terms. It was able to interpret open-ended text, infer connections, and generate structured outputs that reflected nuanced understanding. This capability enabled synthesizing regulatory language into framework-friendly indicators, extracting user needs from loosely structured interviews, and aligning inventory tool descriptions with stakeholder goals and regional policy requirements.

3.3.2. Implementation

The implementation of the LLM-based consultant followed a controlled, task-specific process designed to ensure transparency, reliability, and ethical integrity (Figure 1). While the model played an instrumental role in organizing and interpreting WP2 data, its deployment was carefully structured to align with Digi4Live's commitment to human oversight, data protection, and responsible AI use.

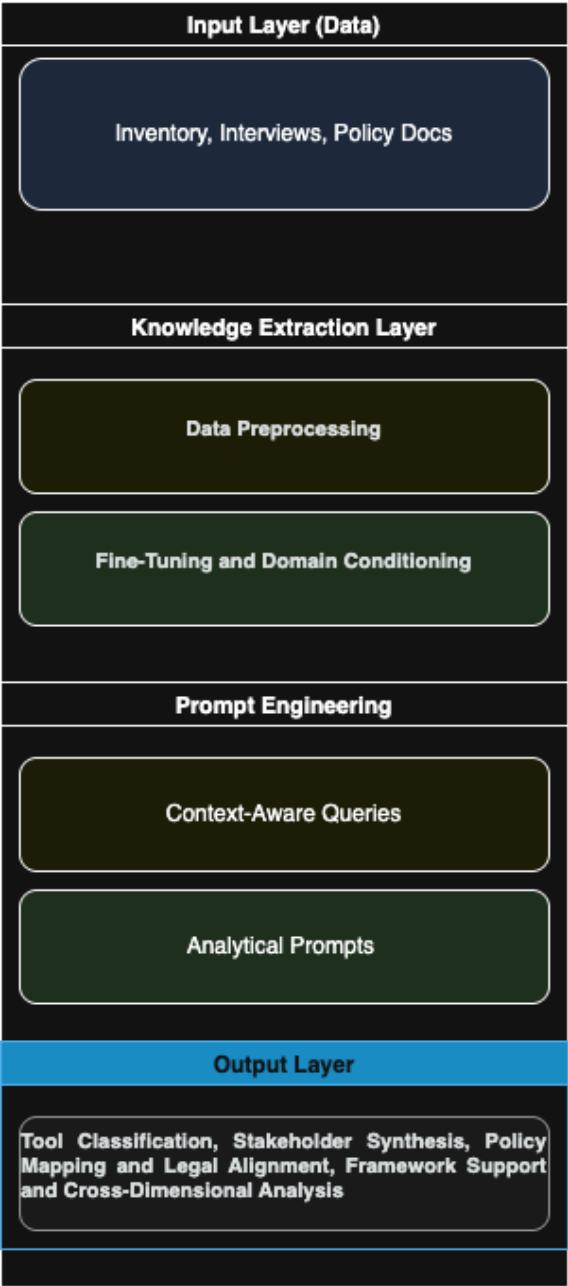


Figure 1. Digi4Live Large Language Model (LLM) assistant pipeline.

Model selection

The AI consultant was built using Meta’s LLaMA 2 (Large Language Model Meta AI), a leading open-source LLM released under a research-use license. LLaMA 2 was selected because of its i) multi-domain query handling which enabled cross-referencing between heterogeneous inputs such as digital tool specifications, interview narratives, and legal documents, critical for synthesizing WP2 findings; ii) Fine-tuning compatibility, which allowed project-specific adaptation using Digi4Live datasets, enhancing the model’s sensitivity to agricultural vocabulary, regulatory nuances, and stakeholder context; iii) Output explainability, which facilitated interpretation and validation of responses, ensuring transparency in how analytical insights were derived, an essential requirement for methodological credibility; and iv) its open-source nature and configurability allowed adherence to EU principles for trustworthy AI, including transparency, fairness, and human oversight (i.e. ethical alignment).

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To maintain full control over data security and usage, LLaMA 2 was deployed in a self-hosted, offline environment, ensuring that no sensitive project data was shared with third-party services or external APIs. This setup was compliant with the Digi4Live data protection policy and GDPR obligations.

Fine-tuning and domain conditioning

To align the model with the Digi4Live context, a parameter-efficient fine-tuning strategy was adopted using LoRA (Low-Rank Adaptation), a method that allows selected layers of the model to be updated while keeping the base model weights frozen. This approach significantly reduces resource demands while still enabling high-quality adaptation.

The model was conditioned using curated, structured content from three primary sources: i) T2.1 inventory data were descriptions of digital tools, structured by function, species focus, TRL, interoperability, and use-case relevance. ii) T2.2 thematic summaries were synthesized insights on adoption drivers, barriers, digital readiness, and stakeholder roles, prepared from interview analysis. No raw transcripts or personal data were included in the analyzed dataset. ii) T2.3 regulatory excerpts were segments of GDPR, the Data Governance Act, AI Act, and relevant national laws, adapted into short, context-rich prompts and knowledge pairs for training. This conditioning ensured the model internalized the terminology, logic, and structure of the Digi4Live evidence base, improving relevance and interpretability of outputs.

Software and hardware requirements

To minimize the costs and complexity, training was conducted using LoRA techniques and quantized model weights. The technical requirements regarding the software stack were:

- transformers and peft libraries (HuggingFace ecosystem),
- LoRA implementation via peft for efficient adapter training,
- Mixed-precision support with accelerate for optimized memory use.

Hardware requirements (minimum setup) for running the LLM were 1 x NVIDIA RTX 4090 (24GB RAM) GPU and 500GB SSD storage (to store model weights, adapter checkpoints, training data). LoRA fine-tuning reduced training time and GPU memory usage, making this setup feasible for an academic environment without high-performance computing clusters.

Input and output design

The fine-tuned model was integrated into a structured prompt-response pipeline tailored to the analytical demands of Work Package 2. A wide array of structured queries was designed to support the synthesis of findings from Tasks T2.1, T2.2, and T2.3. These queries reflect real analytical needs in the areas of tool classification, stakeholder synthesis, policy alignment, and framework dimension development. Representative prompts are presented in Table 2.

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Table 1: Representative prompts in the areas of tool classification, stakeholder synthesis, policy alignment, and framework dimension development.

Area of assessment and representative prompts
Area: Tool classification "List tools suitable for extensive sheep systems with low broadband availability." "Group digital tools by main function: welfare monitoring, emissions tracking, and traceability." "Which inventory entries show potential for reuse in public administration settings?"
Area: Stakeholder synthesis "Summarize the most common barriers to digital adoption for mid-size dairy farmers." "Cluster stakeholder needs related to animal health monitoring tools." "What digital training gaps are reported by farmers in mountainous or remote areas?" "Extract all stakeholder expectations related to data-sharing security." "Summarize perceived benefits and concerns from tech providers versus public authorities."
Area: Policy mapping and legal alignment "Identify key GDPR constraints related to data collected from on-animal sensors." "Highlight regulatory differences between national frameworks that affect data sharing." "What elements of the EU Data Governance Act are most relevant for AI-based livestock tools?" "Summarize stakeholder references to regulatory uncertainty in the interviews." "Map which policy barriers most frequently affect small-scale farming systems."
Area: Framework support and cross-dimensional analysis "Create matched pairs between tool functionalities and reported stakeholder needs." "List common design limitations affecting usability across multiple tools." "Identify cases where regulatory barriers align with stakeholder concerns." "Suggest improvement strategies based on clusters of low adoption and high usability."

Ensuring human oversight, transparency and bias management

The use of the LLM was embedded within a rigorous process of human validation, ethical review, and iterative feedback. At all times, the AI served to support, not replace, expert judgment. All outputs were reviewed by at least two analysts with domain expertise. AI suggestions were cross-checked with original documents or inventory entries. No unsupervised text generation or autonomous conclusions was permitted. Transparency and traceability of results were ensured and model logs were maintained to track prompt formulation and versioned data sources. Bias detection and correction was also conducted.

When carrying out the analysis, the authors tested for and flagged overrepresentation of dominant tools or companies, monitored for skewed treatment of farm types (e.g., emphasis on intensive over extensive systems), and checked the results for regional imbalance or oversimplification. Prompt engineering was iteratively adjusted to ensure representative, context-sensitive responses.

Regarding ethical aspects, no personal or sensitive data were processed by the model. All conditioning data used by the model were either public, anonymized, or formally approved for analytical use. The AI system operated in line with EU guidelines on trustworthy AI, emphasizing human agency, fairness, and accountability.

In summary, the LLM-based consultant enabled the authors to manage complexity, maintain analytical integrity, and extract structured insight from diverse evidence. It made the construction of a coherent, evidence-based, and scalable framework possible, but it did so as a background instrument, always under expert direction, and never autonomously.

3.3.3. Remarks about the benefits and opportunities of LLM for wider use

The integration of a fine-tuned, domain-adapted LLM-based consultant in the analysis of WP2 demonstrated substantial benefits, both in terms of immediate analytical gains for Deliverable 2.3 and in laying the

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groundwork for future applications in the project. Used as a scalable, expert-guided assistant, the LLM offered capabilities that extended beyond those of traditional document review or manual coding. It made the processing of large and complex data feasible and enhanced the depth, speed, and consistency of insight generation. The benefits could fall under three aspects presented below.

1. Scaling analytical capacity

One of the LLM's most important contributions was its ability to scale the project's analytical reach. It enabled rapid classification and synthesis of hundreds of inventory items, dozens of stakeholder input summaries, and multiple policy texts across languages and sectors. By translating qualitative narratives into structured insight, the LLM made it possible to build a comprehensive framework without sacrificing contextual detail. This scalability is especially crucial in cross-country research, where heterogeneity of input often slows down comparative analysis. The model effectively extended the team's capacity to think across scales, from individual farm-level concerns to EU-wide policy implications.

2. Enabling policy-relevant insight in real time

The LLM enhanced the consortium's ability to link stakeholder and tool-level analysis with evolving EU policies. It supported identification of which solutions align with regulatory instruments like GDPR, the Data Act, or the AI Act, where policy gaps or misalignments exist (e.g., unregulated use of AI in animal welfare) and how different user groups interpret and respond to data-related rules or ethical concerns. This enabled the framework and methodology to remain technically robust and legally and institutionally valid.

3. Enabling future applications across Digi4Live

The LLM-based methodology sets a foundation for interactive, user-centered tools in upcoming project phases: In **WP3** the semantic mapping capabilities of the LLM could support further scenario planning, tool matchmaking, or participatory evaluation during co-design activities with farmers, advisors, and innovators. In **WP5** it could strengthen the ability to rapidly analyze qualitative feedback and regulatory texts can support continuous monitoring of outcomes of case studies, including regional uptake trends and user satisfaction. In **WP6** an LLM-informed logic can be embedded in digital toolkits or dashboards, helping policymakers or SMEs query tailored insights (e.g., "Which tools are GDPR-compliant and low-cost for small ruminants?"). In **WP1**, **WP4** and **WP8** it can ensure that exploitation efforts are grounded in actual user contexts and systemic realities, allowing the strategy to focus on viable pathways for uptake, market readiness, and long-term value creation. These forward-looking insights show the potential and adaptability of an AI-supported framework architecture for upcoming Digi4Live's Work Packages.

When used responsibly, the LLM transforms static and fragmented project data into dynamic, structured insight. It serves as a transparent bridge between innovation and regulation, stakeholder needs and digital solutions and qualitative experience and strategic policy goals.

By helping to reveal patterns, align expectations, and track compliance conditions, the LLM can accelerate research and amplify the precision, inclusiveness, and actionability of the analysis. As Digi4Live progresses into co-creation, impact measurement, and dissemination phases, results established through the LLM-supported methodology offer a scalable model for digitally enhanced, expert-led decision support across the livestock innovation landscape.

4. Results

4.1. Innovation readiness and tool adaptability

This section presents the findings generated through the application of framework presented in section 3. The findings are grouped thematically around four interrelated domains: innovation readiness, stakeholder needs, policy and legal barriers, and systemic enablers and blockers.

The analysis of over 370 digital tools and datasets from the Digi4Live inventory revealed a nuanced landscape of technological maturity and deployment constraints in the European livestock sector. By using a fine-tuned LLM, we were able to systematically classify and cross-reference tools by Technology Readiness Level (TRL), species focus, system compatibility, and infrastructural requirements. This allowed for a multi-dimensional understanding of digital tool readiness and adaptability, which fed directly into the framework dimensions.

The key findings were related to themes “high TRL, low transferability”, fragmentation by species and functionality, poor interoperability and integration, insufficient design for rural conditions and evidence of bottom-up repurposing as summarized below.

High TRL, low transferability: Tools such as Afimilk, SCR Heatime, and MooMonitor+ demonstrate commercial maturity (TRL > 7) and are widely used in intensive dairy systems. However, their narrow species and system scope limits their adaptability to other contexts like extensive sheep or goat farming. This restricts cross-sectoral benefits and limits reuse in mixed farming systems.

Fragmentation by species and functionality: Of the 378 tools and datasets catalogued, nearly 70% targeted dairy cows. Far fewer covered pigs (32.5%) or sheep (16.7%). Application areas were heavily concentrated in health and welfare monitoring (87.8%), with substantially lower uptake in reproduction, grazing, and environmental tracking, functions critical for extensive or sustainability-focused farms.

Poor interoperability and integration: Responses from stakeholder interviews highlighted that many tools lack API interfaces or interoperability features, creating data silos and impeding integration into broader farm management systems. This hinders scaling and joint use in cooperative or multi-platform environments.

Insufficient design for rural conditions: The LLM analysis flagged tools with limited usability in low-connectivity environments and scarce multilingual support. Although some efforts exist, such as SheepIT for autonomous grazing control or FarmCloud for low-bandwidth data capture, these remain the exception rather than the rule.

Evidence of bottom-up repurposing: Stakeholder interviews provided compelling examples of farmers modifying commercial dairy solutions for use in sheep farms. These grassroots adaptations often relied on manual data input adjustments, indicating user-led innovation despite the lack of formal tool support.

Insights summarized above were generated using structured LLM prompts. Representative prompts are presented in Table 3). Outputs were reviewed by domain experts, then mapped to framework indicators such as tool flexibility, integration readiness, and accessibility. The LLM’s ability to semantically cluster and extract these patterns from the inventory and interviews was pivotal in surfacing hidden gaps and cross-context potentials.

Table 3: Representative prompts for innovation readiness and tool adaptability by the area of assessment.

Area of assessment and representative prompts
Area: General tool assessment "Group inventory tools by TRL and identify patterns in maturity by species and application area." "Highlight tools with TRL 7 or above and describe their usage contexts and species limitations."
Area: Adaptability and transferability "List tools designed for dairy systems and evaluate their applicability to sheep or goat farming." "Identify tools mentioned in interviews that were repurposed or adapted by end users."
Area: Interoperability and integration "Which tools in the inventory mention API access or integration with farm management platforms?" "Summarize stakeholder feedback on interoperability challenges with current digital tools."
Area: Usability and accessibility "What inventory tools support offline use or low-bandwidth environments?" "List tools that offer multilingual interfaces or mobile-first design features."
Area: Innovation from the bottom up "Extract examples from interviews where stakeholders adapted tools outside their original scope." "What grassroots innovations were mentioned that indicate unmet needs or design gaps?"
Area: Tool gaps and design limitations "Identify common technical design gaps in tools used in extensive or low-tech livestock systems." "Summarize limitations preventing scaling of AI-based tools from pilot to commercial level."

4.2. Stakeholder needs and grassroots innovation

Key findings

The analysis of stakeholder interviews conducted across nine countries in T2.2 highlighted a wide range of user needs, usability challenges, and grassroots-level innovations in the deployment of digital livestock technologies. Farmers, technology providers, public authorities, and advisors provided insights into their motivations, expectations, and frustrations, forming a multi-dimensional picture of what is required for successful adoption and innovation.

The key findings were related to the themes of usability barriers, training and support gaps, repurposing and adaptation, trust and transparency, innovation from below and skills gap and complexity as explained below.

Usability barriers: Stakeholders frequently pointed to poor interface design, language limitations, and lack of integration with day-to-day workflows as major barriers to adoption, especially for small and mid-sized farms.

Training and support gaps: A lack of user training and after-sales technical support was consistently cited, particularly for complex tools that required regular calibration or data interpretation.

Repurposing and adaptation: In multiple interviews, stakeholders reported informal practices of repurposing tools. For example, a dairy monitoring system was adapted for sheep herds in Greece, and traceability data was reused for local environmental reporting.

Trust and transparency: Concerns about data ownership and the unclear terms of service for cloud-based solutions were widely shared. Stakeholders emphasized the need for transparent data governance.

Innovation from below: Grassroots actors often drove innovation by combining open-source tools with local practices, demonstrating a need for flexible and modular systems.

Skill gaps and complexity: Many users indicated they lacked the training or support to use digital tools effectively.

Representative LLM prompts

Representative LLM prompts followed by their outputs supporting these findings are presented below.

Prompt: "Summarize stakeholder concerns related to usability of digital livestock tools from the T2.2 interviews."

Output: "Users across different European countries cited unclear interfaces, missing translations, and incompatibility with legacy hardware as key frustrations. Smaller farmers were particularly disadvantaged by tools requiring continuous internet connectivity or extensive training."

Prompt: "Identify examples where farmers repurposed digital tools for unintended applications."

Output: "In the Thessaly region, farmers modified a dairy-focused health monitoring tool to track feeding behavior in sheep."

Prompt: "Extract themes related to data trust and transparency from stakeholder interviews."

Output: "Participants raised concerns about cloud-stored data being used without consent. Many lacked clarity on who could access or process their data, and requested more transparent governance mechanisms."

Prompt: "Summarize financial obstacles to adopting digital tools from interviews with small-scale livestock farmers."

Output: "Key financial barriers include high initial costs for hardware (e.g., sensors, control systems), recurring expenses for software licensing, and long-term maintenance costs. Some stakeholders also noted indirect costs such as labor time for learning new systems or disruptions during integration."

This was validated by several stakeholder responses where digital adoption was halted due to upfront investment needs and ongoing support costs.

Prompt: "Identify how digital complexity affects adoption among mid-size farms."

Output: "Several interviewees described digital platforms as overly complex, requiring multiple logins, unclear interfaces, or lacking tutorials. Others mentioned staff turnover and lack of digital literacy as long-term barriers."

This aligns with interview data where users indicated partial usage of tools, often ignoring features like automated data analytics or reporting modules.

Prompt: "Extract examples of frustration due to lack of system integration."

Output: "Several farmers described using five or more separate systems for feed, health, and reproduction tracking, none of which shared data. Repeated manual entry was reported as both error-prone and time-consuming."

This was particularly common in mixed-species farms or cooperatives that rely on different vendors or legacy infrastructure.

Prompt: "Synthesize stakeholder concerns around data ownership and digital trust."

Output: "Respondents expressed strong interest in data sharing if safeguards were in place. Concerns included misuse by third-party platforms, unclear data ownership in cloud solutions, and lack of compensation for shared insights."

This input shaped the framework's focus on data sovereignty and helped to highlight ethical priorities in policy recommendations.

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When considering grassroots adaptation, the LLM was effective in surfacing bottom-up innovation stories embedded in interview narratives, as elaborated by this example. Prompt: “Give examples of users adapting or customizing digital tools to local needs.”

Output: “One farmer adapted a cattle health monitoring app for sheep use, while another repurposed traceability data for nutrient runoff monitoring. Informal partnerships with university researchers or open-source communities were also mentioned.”

These insights, generated with LLM assistance and validated through expert interpretation, fed directly into the framework’s indicators on usability, trust, and grassroots innovation readiness. The AI-supported process significantly accelerated synthesis across diverse qualitative inputs and ensured cross-country comparability, providing a robust basis for the design of scalable, user-centered solutions.

4.3 Regulatory fit and legal barriers

Analysis of Task 2.3 outputs confirmed that the regulatory landscape for digital agriculture is dynamic yet fragmented, introducing both enabling and inhibiting forces for livestock projects. The integration of a Law-informed analytical layer via the LLM extended our framework by systematically highlighting key constraints and opportunities tied to evolving legal approaches such as GDPR, the Data Governance Act (DGA), Data Act, and the AI Act.

The key findings and their AI-supported evidence are presented below. The key findings were related to the themes GDPR awareness, implementation uncertainty, emerging data acts, AI act’s risks for animal welfare tools, interoperability standards and to disconnection between supportive policy and digital application.

GDPR awareness, implementation uncertainty

“While GDPR is often mentioned, stakeholders remain unsure how it applies to farm-level data.”

LLM Input Prompt: “Summarize farmers’ questions around GDPR applicability in livestock data contexts.”

Output: “Many farmers ask: ‘Does sensor data about milking or grazing qualify as personal data?’; ‘Who owns the data stored in cloud dashboards?’; and ‘How long can we keep data before it must be erased?’”

Referenced evidence: D2.2 policy review and stakeholder interviews in Northern Europe.

GDPR vs. emerging data acts

“The DGA and Data Act propose constructive data-sharing models such as data altruism and B2G reuse, but remain unexplored by most participants.”

LLM Input Prompt: “Identify mentions of the Data Governance Act or Data Act in stakeholder feedback and note awareness levels.”

Output: “Few interviewees referenced these Acts. Among those who did, comments were: ‘I’ve heard of data altruism, but no one told me how it works,’ or ‘I’m unclear on how B2G data reuse would apply to milk records.’”

Referenced evidence: D2.2 analysis of GDPR implementation barriers.

AI Act risks for animal welfare tools

“Tools using machine learning for welfare or behavioral classification may fall under the AI Act’s high-risk classification, creating uncertainty.”

LLM Input Prompt: “Flag references in interviews to future AI regulation affecting farm animal monitoring tools.”

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Output: “One tech provider stated: ‘If our behavior analysis module counts as decision-making, we may become ‘high-risk’ under AI Act—then certification is costly.’”

Referenced evidence: D2.2 legal gap analysis.

Interoperability standards are weakly applied

“While ICAR and ISO standards exist, adoption is inconsistent across member states, hindering data interoperability.”

LLM Input Prompt: “What do stakeholders say about the challenges of interoperability and lack of standardization?”

Output: “Comments included: ‘Our traceability module uses ICAR, but it doesn’t sync with national vet systems.’ and ‘Some countries require different export formats—it’s a nightmare.’”

Referenced evidence: D2.1 catalog metadata and D2.2 interviews

Disconnection between supportive policy and digital application

“Rural or farm-level policies (e.g., broadband investment, eco-schemes) do not mention digital tracking—opportunities for integration are lost.”

LLM Input Prompt: “Summarize stakeholder feedback on digital infrastructure or subsidies lacking livestock tracking incentives.”

Output: “Many said they received broadband or CAP eco-support but weren’t told how to apply it to livestock tracking.”

Referenced evidence: D2.2 policy review.

4.4. Gaps, barriers, and areas for improvement

The cross-application of the framework across WP2 outputs highlighted several recurring gaps and barriers that restrict the broader uptake of digital tools in livestock systems (Table 4). The assessment revealed opportunities for systemic improvement. The opportunities included support for open-source, modular tool ecosystems that allow adaptation and localization; funding schemes and public procurement strategies that prioritize interoperable, compliance-ready solutions; Living labs and multi-actor co-creation spaces to surface and formalize grassroots innovation practices; and harmonization of standards and consent protocols to ease cross-border implementation and build user trust.

Table 4: Recurring gaps and barriers identified.

Category	Barrier or gap Identified
Technical	Lack of interoperability; absence of shared data standards; limited offline functionality
Economic	High cost of proprietary tools; lack of funding for pilot trials; unclear ROI for smallholders
Regulatory compliance	Ambiguity on data ownership and responsibility; varying interpretations of GDPR and AI
Social/Cultural	Distrust in technology providers; perceived loss of autonomy; generational divide in adoption willingness
Design/Usability	Inadequate support for multilingual, mobile, or non-expert users; lack of training resources

4.5. Synthesis to identify strategic patterns and recommendations

Five patterns were synthesized from the Digi4Live evidence base using the common framework and AI-assisted semantic analysis. Each pattern is supported by LLM-generated insights linked to actual inventory and interview data from Deliverables 2.1–2.3. The five patterns, LLM-expert dialogue (i.e. prompts and corresponding LLM outputs) and actionable recommendations are presented in this section and in Tables 5–9).

Pattern 1: Fragmented innovation Ecosystem with high latent potential

Pattern 1 (Table 5) revealed that high-quality tools exist, but they remain siloed. User-initiated improvisations point to a missed opportunity for designing for cross-system reusability. Therefore, it is recommended to i) fund interoperable **toolkits**, ii) scale grassroots adaptations via **living labs** and iii) set **open-standard criteria** in R&I funding

Table 5: LLM-expert dialogue for pattern “fragmented innovation ecosystem with high latent potential”.

Prompt	Output (condensed)	Insight Source
"Identify tools from inventory that could be adapted across species or systems."	"Afimilk and MooMonitor+ show high maturity but are limited to dairy. SheepIT shows multi-species adaptability but low TRL."	D2.1 inventory
"Summarize grassroots adaptation cases mentioned in interviews."	"In Spain, a farmer repurposed a dairy collar for sheep herd tracking. Another adapted traceability data for pasture compliance."	D2.1 interviews

Pattern 2: Trust, usability, and support matter more than technological sophistication

Pattern 2 (Table 6) suggested that even advanced tools fail to scale if they don't align with simple user preferences, that are clarity, accessibility, and control. The results therefore lead to a recommendation to i) prioritize **human-centered design**, ii) offer **multilingual, mobile-first interfaces** and iii) to build **community support networks**

Table 6: LLM-expert dialogue for pattern “trust, usability, and support matter more than technological sophistication”.

Prompt	Output (condensed)	Insight Source
"List usability issues reported across interviews."	"Farmers cite poor data visualization, insufficient language support, and lack of mobile app options."	D2.1 interviews
"Extract statements related to data ownership concerns."	"We don't know who owns the data our collars collect, it might go offshore," and "We need clear contracts, not just terms I don't understand."	D2.1 interviews

Pattern 3: Legal and policy uncertainty blocks adoption

Pattern 3 (Table 7) suggested that uncertainty about data rights and regulatory definitions stalls adoption, even when tools are technically mature. Therefore, it is recommended to i) embed **GDPR/GDPR-Act templates** into tools, ii) organize **early-stage legal co-design sessions** and to iii) publish **low-risk AI use guides**.

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Table 7: LLM-expert dialogue for pattern “legal and policy uncertainty blocks adoption”.

Prompt	Output (condensed)	Insight Source
"Highlight GDPR-related uncertainties among users."	"Many ask: Are sensor recordings personal data? How long can we store them? Who can see them?"	D2.1 interviews
"Identify mentions of AI classification concerns under the AI Act."	"If a behavior alert counts as automated decision-making, it could be ‘high-risk’, that means compliance costs."	D2.2 legal review

Pattern 4: Innovation is unevenly distributed

Pattern 4 (Table 8) suggested that digital transformation is often channeled toward well-resourced systems, leaving mixed, remote, or diverse stakeholders behind. It is therefore recommended to i) target **offline-optimized tools**, ii) include **gender and youth lenses** in R&I calls and iii) support **modular solutions** for low-connectivity areas.

Table 8: LLM-expert dialogue for pattern “innovation is unevenly distributed”.

Prompt	Output (condensed)	Insight Source
"What infrastructure or demographic barriers are mentioned?"	"Southern farms struggle with broadband; language barriers are common. Women-led farms note interface complexity."	D2.1
"Identify underrepresented user segments in inventory tools."	"Sheep/goat tools make up 20%, but actual extensive systems require broader support."	D2.1 inventory

Pattern 5: The system needs connective infrastructure, not just more tools

Pattern 5 (Table 9) suggested that tool proliferation alone doesn’t translate into scaled value unless they are connected, trusted, and manageable within the whole system. It is therefore recommended to i) build **integration hubs & APIs**, ii) launch **federated data systems** and iii) to deploy **AI assistants for real-time support**

Table 9: LLM-expert dialogue for pattern “the system needs connective infrastructure, not just more tools”.

Prompt	Output (condensed)	Insight Source
"What do stakeholders need beyond individual apps?"	"We need dashboards that integrate multiple data streams, not five separate apps with duplicate data entry."	D2.1 interviews
"Summarize developer requests for testing environments."	"Pilot environments and sandbox APIs would help us test interoperability without risking real data."	D2.1 interviews

5. Conclusion

This deliverable represents a synthesis of the Digi4Live WP2, translating the data, perspectives, and legal frameworks collected in Tasks 2.1, 2.2, and 2.3 into a unified analytical output. The development of a common framework, built on seven analytical dimensions, enabled a structured and context-aware assessment of digital solutions and stakeholder realities across Europe's diverse livestock systems. By integrating this framework with an AI-augmented analysis process, powered by a fine-tuned Large Language Model (LLM), the team was able to extract deeper insights from complex and heterogeneous data. The AI assistant played a supportive but significant role, enabling semantic clustering, pattern detection, and dynamic cross-referencing across the full WP2 evidence base. All outputs were subject to expert review, ensuring transparency, contextual accuracy, and ethical compliance. The findings confirm that while digital innovation in livestock farming is active and growing, it is also fragmented, unevenly distributed, and often constrained by trust between actors, usability of digital tools, and legal uncertainties.

The deliverable identifies five strategic patterns that shape the current and future state of digital agriculture, each accompanied by actionable recommendations that can inform subsequent phases of the project. Five strategic patterns elaborated in the previous section spotlight critical system-wide levers, from tool interoperability and trust-building to ethical alignment and infrastructure development. By addressing them, the project ensures that co-creation and evaluation (WP3, WP5) of digital concepts and policy engagement (WP6, WP7) are grounded in real-world dynamics, scalable innovation, and equitable access, aligned with technological opportunities, stakeholder diversity and responsibility of innovation. This synthesis is reflection of what exists and guidance for where the livestock sector can and must go next in its digital transformation that is systemic, inclusive, and sustainable.

