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Invited Review Article

"Please, mind the gap": A narrative review on digitalization gaps and barriers in the livestock sector

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ABSTRACT

The livestock sector generates large volumes of data; however, these data remain underutilized. The Data Governance Act, the Data Act of the EU, and recent technological advances, provide an opportunity to automate and improve collection, integration, and use of livestock data. Data spaces, as secure and interoperable environments for data sharing, offer a promising framework to support this transformation. However, this can only be achieved by removing implementation barriers to data sharing and new data generating technologies. The aim of this paper is to provide an overview of key digitalization barriers and gaps in livestock sector. We synthesized existing knowledge across five topics: 1) interoperability, 2) economic viability, 3) technical skills, 4) data privacy and security, and 5) data robustness and quality. Finally, a narrative on how these gaps could be bridged was provided. We argue that bridging these gaps requires a holistic approach combining training, trust building, data governance, and collaboration. EU-level initiatives and projects address some of these areas, but better coordination is needed to maximize impact. The Data Act provides a regulatory foundation for data sharing, yet its limitations, such as its horizontal nature, narrowly defined or unclear terms and exclusion of insights derived from product and related service data, leave critical gaps and may lead to legal disputes. To overcome persistent data lock-in, proactive negotiation, public APIs, and an update on a voluntary industry code of conduct to align with the Data Act are essential for fostering transparency and accelerating adoption of digital solutions.

1. Introduction

Digital technologies are transforming our society, making the implementation of data-driven food systems imperative. Instead of single point observations, digital technologies enable continuous, real-time monitoring of animals at scale. Better use of big data, combining data from different domains, and artificial intelligence (AI) are a big opportunity to improve livestock sector's efficiency and the overall sustainability of food systems.

Across and beyond food systems, there is a sharp increase in the number of smart connected objects (e.g. machinery, robotics, sensors), which offer increasing amounts of data processing and analytical capacity. Combining data from multiple sources has a high potential to add value to the livestock sector; however, the cost of new technologies may be prohibitive unless effectively used. Besides economics, significant barriers for efficient data use include poor standardization, rules on

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storage and sharing of datasets, and ethical and privacy concerns related to data sharing. Relevant data are often held by a variety of actors (e.g. farmers, authorities, abattoirs), which are unable or unwilling to share data automatically. For example, sensor data generated on farms are often locked into proprietary farm management systems and cannot be automatically reused for regulatory reporting, advisory services, or downstream processing due to a lack of interoperability and unclear data access rights. Farmers and authorities often need to manually input the same data in several systems such as farm management information systems and subsidy applications. However, the situation is expected to change rapidly; the European Union's (EU) recent Data Governance Act (European Parliament and Council, 2022) sets rules for (re)using certain protected data held by public sector bodies, for companies providing data intermediation services, and for data altruism (sharing data voluntarily for no reward). Such data has huge potential to advance research and lead to better governance, products and services. In this context, data spaces, secure and interoperable environments for data sharing across sectors, are emerging as key enablers of trusted data exchange and collaboration (Kovach et al., 2026). Moreover, the Data Act (European Parliament and Council, 2023) aims to make industrial data more accessible and usable, foster innovation, increase data availability, and ultimately enhance EU's data economy. Together, these examples illustrate that barriers to livestock digitalization are not purely technical, but arise from persistent interoperability failures, fragmented responsibilities across actors, and unresolved regulatory and governance questions (OECD, 2020).

Hence, we now have a great momentum to boost the exploitation of livestock digital technologies. Digitalization and precision livestock farming have been extensively addressed in the literature through reviews examining specific technologies (e.g. Gómez et al., 2021), adoption drivers and barriers (e.g. Dibbern et al., 2024; Kroupová et al., 2025; Mallinger et al., 2024), and data–related challenges (e.g. Ruder and Wittman, 2025). However, existing reviews tend to address fragmented aspects of digitalization, such as species–specific contexts or isolated economic, technical, or behavioural dimensions, rather than integrated value–chain implementation challenges (e.g. Gómez et al., 2021; Langer et al., 2024; Lovarelli et al., 2020; Stygar et al., 2021). Moreover, regulatory developments, data governance arrangements, and evidence from grey literature, often central to real–world implementation and decision–making, are only partially addressed in the academic literature and are frequently examined from single disciplinary perspectives, such as economics, ethics, or data governance (e.g. OECD, 2020).

Consequently, the literature lacks integrative synthesis that jointly examines technical, economic, socio–organizational, and regulatory barriers to digitalization across the entire livestock value chain, while explicitly situating these barriers within the evolving EU data governance framework.

With the above background in mind, our research questions are as follows:

1) What are the biggest implementation gaps and barriers to digital technologies in the livestock sector?
2) How could we effectively bridge identified gaps?

For this study, a narrative review was adopted. A narrative approach allowed the integration of heterogeneous evidence sources, grey literature, and expert insights, which is essential for examining complex gaps and barriers that are not fully captured in peer–reviewed literature.

The conceptual framework guiding our methodology is presented in Fig. 1.

First, a multidisciplinary group of experts in precision livestock farming, law, economics, production technologies, system analyses, biosystems engineering, and livestock production provided contributions on key gaps and barriers in implementing digital technologies in the livestock sector. These experts collaborated as co-authors of this study within the framework of an EU-funded project Digi4Live (https://digi4live.eu/). Second, these insights were complemented by stakeholder engagement, including 52 semi-structured interviews with relevant stakeholders and Digi4Live project webinars. Interviewed stakeholders were software developers technology providers or users, the latter included among others industry actors (e.g. breeding companies, dairy companies, slaughterhouses retailers), public authorities, farmers and farmer organizations, farmer consultants, and research institutes (Bartzanas et al., 2025). This step contributed to identifying practical implementation challenges and emerging issues that have not yet been extensively captured in peer-reviewed literature. Finally, where possible, the identified gaps and barriers were supported by evidence from peer-reviewed and grey literature. Databases such as Web of Science, Scopus, and Google Scholar were consulted, with keywords taken from the interviews, and the search focused on literature published over the past decade. The literature screening was conducted in two stages. First, relevant studies were identified based on title and abstract screening. Subsequently, full texts were reviewed to ensure relevance. The review process was organized by thematic areas, with dedicated author teams responsible for each topic: (1) interoperability (TN, AS, MP), (2) economic viability (AS, JN), (3) technical skills (VA, TB, SV, GA), (4) data privacy and security (HK, AMC), and (5) data robustness and quality (AL, CA, AS). Each team independently examined the available literature within their thematic domain and identified key gaps, barriers and potential solutions. Following this, an additional review round was conducted in which all co-authors jointly assessed the full manuscript to ensure consistency, coherence, and comprehensive coverage across themes.

To structure the analysis, we distinguish between two key dimensions. First, we build on the previously defined thematic areas: interoperability, economic viability, technical skills, data privacy and security, and data robustness and quality, to categorize the identified barriers. Second, we differentiate between levels of analysis by distinguishing between farm-level and value chain-level perspectives. Building on this structure, a narrative is then presented on how to

Fig. 1. Conceptual framework of the methodology applied in this narrative review.

effectively bridge these gaps and enable a single European market for livestock data. Finally, conclusions with practical recommendations and future directions are provided.

2. What are the biggest implementational gaps and barriers in livestock digital technologies?

2.1. Definitions

The following definitions were used in this article:

A gap is an area where more research or development is needed; i.e. a gap represents the space between where we currently stand and where we want to be. In some cases, such as in very novel areas, a knowledge gap can exist without clear or easily identifiable barriers.

A barrier is an obstacle that prevents progress. In our study 'barrier' refers to the limitations which cause gaps and/or hinder efforts to address an existing gap. In practice, one could imagine a gap without a barrier. A barrier always relates to a gap.

A solution is an approach, measure, or technology that aims to reduce or close a digitalization gap in the livestock sector by addressing the underlying barrier(s) that limit progress. Solutions may be existing, emerging, or conceptual, and can be technical, organizational, or policy-based.

2.2. Digital adoption in Europe's livestock sector – Current situation

Digitalization in the livestock sector has evolved over the past decade from the adoption of stand–alone automation tools and sensors toward more interconnected systems that generate increasing volumes of data across farms and value–chain actors (Sharma et al., 2026), while recent advances in artificial intelligence and data–driven approaches have further expanded this potential by enabling predictive health monitoring, behaviour analysis, and automated decision–support tools (Distante et al., 2025; Guo et al., 2026).

Digital technologies are already widely applied across EU farms (European Commission. Joint Research Centre., 2025). However, their adoption varies significantly among different types of enterprises. For instance, digital technologies are predominantly used in dairy farming, compared to small ruminants, beef, poultry, or pigs (Gómez et al., 2021; Groher et al., 2020; Stygar et al., 2021). These disparities are largely due to differences in technology readiness levels and market availability among species (Gómez et al., 2021).

Farm size and regional characteristics also influence adoption patterns. In particular, there are differences between small-scale and large-scale farming regions, with farms in the former showing increasing interest in adaptation (Gabriel and Gandorfer, 2023). This reflects a broader digital divide between high- and low-technology farms. For example, dairy farms in European countries with high labour costs and intensive production systems increasingly rely on automatic milking systems and animal monitoring sensors (Ferrari et al., 2022). In contrast, many small farms and those operating under extensive, pasture-based systems are characterized by low levels of innovative solutions and limited investment in technology (Bacco et al., 2019).

Over the past decade, the uptake of digital technologies among farmers has surged significantly. A recent survey of French dairy farmers (Nicolas et al., 2024) found that 92 % of dairy farms now utilize at least one digital tool, such as embedded sensors, robots, or automated systems. Specific technologies include estrus detection systems (49 %), milking robots (31 %), automatic concentrate feeders (56 %), cameras (35 %), and milk meters (47 %). Compared to the 2015 survey (Allain et al., 2017), these figures represent more than a twofold increase. At the same time, several technologies that were nearly absent a decade ago have emerged, including feed pusher robots, drones, weather stations, and feeding monitoring systems.

The adoption of digital technologies is largely driven by farmers' own initiative, influenced by both perceived benefits and challenges (European Commission. Joint Research Centre., 2025). Dairy farmers perceive time savings, improved working conditions, enhanced job attractiveness, and better technical performance as key advantages (e.g. Hostiou et al., 2017; Nicolas et al., 2024). On the other hand, farmers mentioned lack of interoperability, concerns over data misuse, inadequate network coverage and increased mental workload as major drawbacks (Hostiou et al., 2017; Nicolas et al., 2024). For those not yet equipped, barriers to adoption include high costs, operational complexity, and the time required for data analysis.

Alongside farm-level adoption, digitalization is also advancing among other actors within the agri-food value chain, including technology providers and food processing companies. Digital platforms and data-sharing infrastructures are increasingly shaping the organization of agricultural data ecosystems (Runck et al., 2022). For example, initiatives such as the John Deere – DeLaval milk sustainability center,[1] or a neutral data exchange platform DjustConnect[2] illustrate various efforts to stimulate effective data use in the agri-food sector. In addition, the EU is actively developing sector-specific data spaces to enable secure and interoperable data exchange across agri-food value chains. EU funded initiatives, such as AgriDataSpace and the Common European Agricultural Data Space (CEADS) aim to create trusted environments for sharing and processing agricultural data, aligned with the EU Data Strategy (European Commission, 2020) and GAIA-X[3] principles. These systems have the potential to support standardized governance, technological sovereignty, and data interoperability, while fostering innovation across farms and related industries. Importantly, such systems could also address current gaps in data utilization. For example, the use of sensor technologies to provide animal welfare information within quality assurance schemes is still limited (Stygar et al., 2022), despite the potential to leverage such data for consumer communication (Ingenbleek and Krampe, 2022). Digital data can also enhance administrative efficiency in agriculture by enabling secure, standardized data sharing for compliance, reporting, and policy monitoring; however, its utilization in these areas remains low (European Court of Auditors, 2022).

2.3. Gaps and barriers

2.3.1. Gaps and barriers to digital technologies concerning interoperability

Interoperability is the ability of systems to exchange and use data within a data space or between two or more data spaces (DSSC, 2025). Interoperability can be achieved at different layers: technical, semantic, organizational, and legal; this article examines gaps and barriers across all these dimensions. Interoperability and standardization are intrinsically linked, as standardization provides common rules and frameworks that make interoperability possible. Without agreed standards for data formats, communication protocols, and semantic definitions, systems cannot reliably exchange or interpret information. Standardization goes far beyond involvement of technology producers since standards are not only technical specifications, but they represent also social, technical, economic, political, and legal activity (Cargill, 2011). The process of standardization typically originates from three primary sources: formal standardization bodies, market dynamics, and governmental regulation (Viardot et al., 2021). In the case of digital technologies related to livestock, all three sources are likely to enforce common specifications. However, the government provides mostly the general standards (e.g. the General Data Protection Regulation (**GDPR**) (European Parliament and Council, 2016), while more technical standards need to be addressed in collaboration with private sector (e.g. ICAR groups, COPA-COGECA).

Recent years have seen significant developments in data management and integration, but several gaps and barriers remain. The gaps

[1] https://www.milksustainabilitycenter.com/.
[2] https://djustconnect.be/en.
[3] https://gaia-x.eu/what-is-gaia-x/vision-and-mission/.

and barriers identified in Table 1 primarily occur at the value-chain (and system level), rather than at the farm level. They reflect structural challenges such as lack of common standards, fragmented data ecosystems, and restricted data access, which affect interoperability across species, regions, and stakeholders.

Among livestock sectors, dairy has achieved a higher degree of standardization compared to other species, largely due to long-standing coordination by the International Committee for Animal Recording (ICAR). ICAR has developed norms and guidelines for animal identification, performance recording, and device/test certification. A recent example is the Animal Data Exchange specification, which provides a unified application programming interface (**API**) for exchanging milking-robot data across vendors, thereby facilitating cross-system data use in herd management and analytics (ICAR Animal Data Exchange, 2025). By contrast, analogous sector-wide standardization efforts for pigs and poultry are largely absent, creating a species-specific disparity in interoperability readiness and slowing cross-farm, cross-platform analytics in those sectors. Interoperability, especially in software, can also be provided by individual software companies by e.g. interfacing similar data sources from different manufacturers and presenting or analyzing those to a user in a unified way. This is the idea behind API ecosystems. (Howie et al., 1997). Using an API ecosystems requires access to APIs from each such system and commonly also managing credentials and access rights by the user. Only a limited number of technology companies in the livestock technology sector provide broad API access to their data for the users (e.g. Habib et al., 2024; Lely, 2025) thus effectively limiting third party interoperability solutions being developed under explicit bilateral contracts. The decision to not to provide access to data can be a part of business strategy or a cost saving measure. In any case, lack of access to data prevents third party software developers from developing improved user interfaces or decision-making algorithms, which could compete with the technology providers' own solution.

Technical interoperability depends on syntactic standards for data transport, while semantic interoperability requires standardized vocabularies and data models to ensure shared meaning. Therefore, the standardization of devices that employ proprietary AI algorithms to process the data provides another layer of complexity. For example, most sensors for measuring animal behavior rely on predictive models, which may measure the same trait, e.g. rumination or feeding time, with a different algorithm. Such devices provide evident potential for use in animal breeding, for example to select more resilient animals if their output can be standardized and validated (Brito et al., 2025; Friggens et al., 2022). There are at least around 40 different accelerometer solutions for dairy cow behavioral monitoring on the market (with various appendage attachment points). Those devices are at different levels regarding validation and can provide various outputs, for instance active vs. non-active or more granulated, like lying, standing, walking (Stygar et al., 2021). In addition, farming systems vary across countries, regions or producers (Saint-Cyr et al., 2017). This fragmentation of the livestock system has led to problems in finding common standards for different digital solutions (already implemented or under development).

To create an adaptable standard, there is a need for a broader collaboration between different stakeholders, including technology producers, standardization bodies and different umbrella organizations (such as COPA-COGECA, which represents more than 22 million farmers in the EU or The European Forum of Farm Animal Breeders, which represents the animal breeding and reproduction organizations). Results presented in Table 1 indicate that interoperability gaps span multiple interoperability layers: technical gaps dominate in sensor standardization and data collection practices, semantic gaps arise from missing annotation standards, organizational gaps relate to insufficient system-level coordination and lack of data-sharing ecosystems, while legal aspects emerge in restricted data access and unclear governance frameworks. Addressing interoperability therefore requires a multi-layered approach rather than isolated technical fixes.

Table 1
Interoperability gaps and barriers to digital technologies in the livestock sector.

Gaps	Barriers	Solutions
Lack of common standard for sensor technologies and performance matrixes, like various productivity, health and welfare indicators (e.g. slaughterhouse findings are not easily comparable even within the same country).	(1) Livestock sector is fragmented making it challenging to implement uniform standards across different countries, regions, farm types, producers (e.g. Saint-Cyr et al., 2017; Stygar et al., 2021).	(1) Provide clear definitions by relevant standardization organizations (e.g. ICAR-IDF initiative (Egger-Danner et al., 2024)). (2) Developed protocols for standardized data integration, especially for pigs and poultry.
Insufficient system-level perspective in defining livestock data standards.	(1) Lack of interest/ resources for standardization from livestock sector.	(1) ISO committees have historically prioritized other sectors, for instance crop production over livestock, resulting in limiting relevance of existing standards (SAG-SF, 2023). Establish species-specific subcommittees to address livestock-specific standardization.
Lack of standards in data annotation for livestock applications	(1) Fragmented data sources and heterogeneous formats, lack of initiative from technology producers	(1) Initiative ongoing in ISO/TC 347 Data-driven agrifood systems. However, focus on livestock is unknown[a]. (2) Some new initiatives, e.g. SENSTARA – EAAP Working Group on Sensors and Standards Development for Research Activities[b].
Insufficient data valorization.	(1) Restricted data access by technology providers limits third-party innovation (narrow API access)	(1) Implement EU Data Act provisions through sector-specific guidelines.
Absence of data-sharing ecosystems and intermediary services.	(1) High barrier to develop new applications as access to data is currently difficult and expensive. Information inequality (Hackfort, 2021).	(1) Technical solutions to lower the cost and increase fair use of data, such as data space standards and software (IDSA[c], GAIA-X[d]). (2) Pilot and demonstration projects (e.g. CEADS[e]). (3) Emerging sector–specific initiatives such as IDDEN[f] and djustconnect[g] demonstrate early solutions.
Inconsistency in data collection and management practices.	(1) Fragmentation of livestock sector-numerous stakeholders including farmers, suppliers, and regulators (Williamson and Leonelli., 2023). (2) Lack of interoperability practices.	(1) Harmonizing data standards and adopting shared data–exchange platforms, broader implementation of guideline principles, such as FAIR (Delavenne et al., 2025) and ontology–based approaches to enable semantic interoperability (Noor et al., 2026)

[a] https://www.iso.org/committee/9983782.html.
[b] https://eaap.org/two-new-eaap-working-groups-established/.
[c] https://internationaldataspaces.org/.
[d] https://gaia-x.eu/what-is-gaia-x/vision-and-mission/.
[e] https://ceads.eu/.
[f] https://www.idden.org/.
[g] https://djustconnect.be/en.

2.3.2. Gaps and barriers to digital technologies concerning economic viability

The market for livestock technologies, particularly in the dairy sector, is already rich in sensor-based solutions (Stygar et al., 2021). Despite this extensive market presence, persistent gaps remain regarding the economic viability of these tools, especially at the farm level (Table 2). This concern is also reflected in farmers' perceptions, as they identify the high cost of digital technologies as a main barrier to adoption (European Commission. Joint Research Centre., 2025). Existing literature provides examples of economic efficiency associated with application of digital tools in livestock systems (e.g. Edwardes et al., 2022; Langer et al., 2024; Moyes et al., 2014; Silvi et al., 2021; Steeneveld et al., 2015; Van De Gucht et al., 2018). However, systematic evaluations capturing overall trends, consistency of outcomes, and sector–wide economic effects, for both researchers and end-users, are still missing. Furthermore, the adoption of digital tools among smaller farms remains low and uneven. While advanced systems such as automated milking or feeding robots are less common among smaller farmers, tools like heat and calving detection are already wider implemented (e.g. Nicolas et al., 2024). These challenges highlight structural issues that go beyond individual farms. As the number of sensor products and data initiatives, such as common data spaces, continues to grow, more systemic barriers emerge across the entire value chain, including questions about scalability, and equitable distribution of benefits. Therefore, the identified gaps reveal a dual focus in digitalization challenges: farm-level versus value chain-level. In addition to conceptual gaps, several practical barriers hinder the implementation of digital technologies. These, at the farm-level, include limited access to economic performance data and the absence of systematic evaluation frameworks, which constrain evidence-based decision-making. High technology costs and concerns about increased workload further restrict adoption on farms. At the value chain level, misalignment of business models and coordination complexity impede the development of data-driven services, while insufficient empirical research on value distribution raises equity concerns (Wysel et al., 2021). These interrelated gaps underscore the need for research and innovation strategies that simultaneously address farm-level adoption barriers and value chain level governance and equity challenges to ensure inclusive digital transformation across the agri-food sector.

Table 2
Gaps and barriers in implementing digital technologies in the livestock sector concerning economic viability.

Gaps	Barriers	Solutions
Insufficient evidence on economic viability of digital tools.	(1) No access to data on economic performance from farms equipped with technology as well as absence of systematic approaches for economic evaluation.	(1) Dedicated research projects to verify claims. (2) Demonstration farms or living labs. (3) Exploring use of Farm Sustainability Data Network (FSDN) data sources. (4) Operational methodologies for estimating return on investment on farms
Limited number of digital solutions implemented on smaller scale farms.	(1) High cost of technology (Bianchi et al., 2022; Langer et al., 2024; Shutske, 2024). (2) Concern on time required to manage data (increase working time) (Abeni et al., 2019).	(1) Promoting open-source solutions. (2) Support scalable systems for gradual adoption– farmers could test on small groups of animals and only make further investment decisions as funds become available. (3) Provide training and funding for proven solutions. (4) Learning from existing EU funded projects like FARMTOPIA[a]
Limited business models capitalizing on the additional value derived from livestock related data.	(1) Misalignment of business logics and coordination complexity (Eustache et al., 2025).	(1) Develop collaborative business models, through ongoing negotiations and adaptations that monetize sensor data through value-added services (e.g., animal welfare certification, traceability, sustainability scoring (Stygar et al., 2023). (2) Develop strong data ecosystem governance structure through clear coordinating roles, responsibilities and value flows (Eustache et al., 2025).
Unequal distribution of benefits among stakeholders (Wysel et al., 2021).	(1) Limited empirical research on how value is distributed in livestock chains when data is shared (Wysel et al., 2021).	(1) Dedicated research project on value creation.

[a] https://farmtopia.eu/farmtopia-navigating-small-farmers-in-the-digital-era/.

2.3.3. Gaps and barriers to digital technologies concerning technical skills

The most important gaps and barriers concerning technical skills are summarized in Table 3. The identified gaps highlight a multi-level challenge in digitalization, centered on knowledge and capacity limitations. At the farm level, constraints include limited ability to manage and interpret data, operate and maintain systems, and understand connectivity technologies, compounded by inadequate technical infrastructure (Bianchi et al., 2022; Drewry et al., 2019; Neethirajan, 2023). Beyond farms, advisory services often lack sufficient capacity to bridge these skill gaps (Bampasidou et al., 2024). At the same time, technology providers and researchers have devoted limited attention to user-centric factors such as perceived ease of use and usefulness (Lima et al., 2018; Michels et al., 2019). A further gap is in the responsibility of technology manufacturers in ensuring farmer competence, as the obligation to provide adequate training and ongoing support as part of the technology adoption remains poorly defined and is not standardized across companies. Also, the identified barriers reflect a multi-level challenge that extends beyond farms to the broader support ecosystem (e.g. limited access to training, usability issues). Importantly, the gaps identified in Table 3 are strongly interrelated rather than independent, pointing to a systemic constraint in which skill limitations, usability challenges, and insufficient support structures reinforce one another. This interdependence suggests that technical innovation on its own is insufficient. Complementary strategies such as capacity building, improved infrastructure, and user-centered design are essential to enable effective and inclusive digital transformation.

2.3.4. Gaps and barriers to digital technologies data privacy and security

With the growing appeal of precision agriculture, farmers are increasingly offered novel digital technologies to enhance the efficiency and sustainability of their livestock farming activities. This literature highlights that these technologies can improve livestock management and welfare, as well as the efficiency of entire food supply chains (Lovarelli et al., 2020). However, there are significant concerns, particularly among farmers, regarding data privacy and security (Grotsch et al., 2025; Krampe et al., 2024). The most important gaps and barriers to digital technologies are pertaining to data privacy and security are summarized in Table 4. The identified gaps occur mainly at the value-chain level, involving multiple actors and processes rather than individual farms. Regulatory inconsistencies, unclear cybersecurity standards, and trust issues among stakeholders are sector-wide challenges that influence data governance and interoperability across the

Table 3
Technical skills gaps and barriers in implementing digital technologies in the livestock sector.

Gaps	Barriers	Solutions
Limited farmer capacity in data management and interpretation (e.g. Bianchi et al., 2022; Drewry et al., 2019;).	(1) Limited access to training programs (Eastwood et al., 2021). (2) Low awareness of how data use can improve decision-making (Drewry et al., 2019). (3) Limited user-friendly tools to visualize and interpret data (Bianchi et al., 2022; Henchion et al., 2022). (4) Poor integration and interoperability among systems (Kopler et al., 2023; Martina et al., 2025).	Develop: (1) localized training programs, (2) visual tools, and (3) demonstration farms to enhance data literacy.
Farmers' low ability to operate and maintain various systems (Bianchi et al., 2022).	(1) Complexity of digital tools and software, user interfaces not designed for farmers (e.g. Bianchi et al., 2022; Daum et al., 2022). (2) Difficulty keeping pace with technology, especially among older farmers; resistance to change and technology discomfort (Drewry et al., 2019; Higgins and Bryant, 2020). (3) Limited technical support and excessive training time (Bianchi et al., 2022; Brier et al., 2020; Eastwood et al., 2021; Higgins and Bryant, 2020).	(1) Design user-friendly devices and intuitive interfaces with minimal setup. (2) Provide hands-on training during deployment and peer-to-peer learning programs. (3) Develop mobile troubleshooting tools and establish local support hubs with trained technicians.
Farmers' limited understanding of connectivity technologies and lack of technical infrastructure (WiFi, IoT, Drewry et al., 2019)	(1) Poor internet and mobile infrastructure in rural areas (e.g. Drewry et al., 2019; Ferrari et al., 2022). (2) Lack of awareness of connectivity's role in technology usage.	(1) Enhance rural connectivity through public–private partnerships. (2) Develop offline-compatible digital tools. (3) Organize workshops explaining connectivity's role in improving efficiency in farming. (4) Invest in rural infrastructure development initiatives.
Insufficient advisor capacity to bridge farmer skill gaps (Bampasidou et al., 2024).	(1) Variability in farmers' level of education, digital literacy and technical skills (job-specific and cross-cutting core), especially in relation to age and flock size (small-medium vs large sized farms) (e.g. Ferrari et al., 2022).	(1) International knowledge exchange and farmer cooperation. (2) Training programs, addressing especially low-educated, small-scale farmers (by using virtual classes, e-learning, and on-site learning) by academia and industry. (3) Taking into account user heterogeneity in terms of education and skills when creating relevant tools; it could help if they were fully automated.
Technology providers' and researchers' limited knowledge / investigation regarding perceived ease of use and usefulness of digital tools by farmers (Lima et al., 2018; Michels et al., 2019).	(1) Limited uptake of tools by farmers; (2) limited involvement of farmers in digital tools' design and assessment (Eastwood et al., 2021).	(1) Integrate participatory design approaches by involving farmers throughout the development process to ensure relevance and usability. (2) Prioritize user-centered design principles.

livestock ecosystem. In contrast, low farmer awareness of security best practices is an on-farm gap, linked to individual knowledge and training.

The adoption of tracking technologies in the context of farms, for instance, naturally requires extensive data collection and processing, generating numerous data points that amplify potential risks concerning farmers' privacy and personal data protection. These risks could contribute to considerable reluctance among farmers to adopt and use these innovations (Kaur et al., 2022). The increasing use of AI techniques (and/or sophisticated statistical analysis to draw patterns) can potentially lead to the breach of farmers' privacy and personal data rights, even in scenarios in which apparent non personal identifiers, such as data on farm practices are collected and processed (Kaur et al., 2022). In addition to the GDPR (European Parliament and Council, 2016), the European Union has adopted new regulations that will impact livestock data processing and sharing namely, the Artificial Intelligence Act (European Parliament and Council, 2024), the Data Governance Act (European Parliament and Council, 2022), and the Data Act (European Parliament and Council, 2023), while the CEADS (https://ceads.eu/) is currently at the deployment phase. On the one hand, these separate legal instruments create a scenario of complexity and legal fragmentation in the governance of data in the EU; on the other hand, these new regulations exhibit inconsistencies, including discrepancies in key terms. For instance, the Data Governance Act uses the term "*general interest*", whereas both the GDPR and Data Act refer to "*public interest*", potentially leading to interpretative confusion. Additionally, the term *"data holder"* is defined differently in the Data Governance Act and Data Act. There is also a lack of clarity around how to distinguish between the roles defined in the GDPR—such as *data controller*, *data processor*, and *data subject*—and those used in the Data Governance Act and Data Act, like *data holder* and *user*. This overlap can lead to confusion about responsibilities and rights under each regulation. Finally, there are unresolved questions about implementation and enforcement, such as how authorities will collaborate to ensure consistent application of these regulations. However, it is noteworthy that the European Commission, on 19 November 2025, published its Digital Omnibus Regulation Proposal (European Commission, 2025a), which aims to streamline and simplify the EU's digital rules, including the GDPR, AI Act, the Data Governance Act, and the Data Act. In particular, it proposes repealing the Data Governance Act except for certain rules, which are proposed to be integrated into the Data Act. While this proposal may undergo substantial changes throughout the EU's legislative process before its adoption as a final, binding regulation, amending the above-listed regulations among others, it remains to be seen whether the final version will address the regulatory inconsistencies. However, as a non-sector-specific proposal, it will likely not shed much light on issues related to data collection, processing, and sharing in the context of agriculture and livestock farming. Thus, based on the current legal landscape (and potentially even after the finalization and adoption of the Digital Omnibus), EU-wide regulatory guidance will be critical, particularly in the context of agriculture and livestock farming.

When a complex regulatory framework is combined with the absence of clear guidelines, standards and best practices for technology providers, and with limited transparency from technology providers regarding data collection, processing, and sharing with third parties, farmers end up in a position where they are uncertain about the protection of their privacy, in addition to not having meaningful information on who process, hold or access data originating from their own farm

Table 4
Gaps and barriers in implementing digital technologies in the livestock sector concerning data privacy and security.

Gaps	Barriers	Solutions
Regulatory inconsistencies between GDPR[a], Data Governance Act, and Data Act, and lack of clear guidance for joint implementation in livestock tracking contexts.	(1) Absence of harmonized interpretation and practical guidelines for compliance across these frameworks.	(1) Develop regulatory guidelines and/or sector-specific guidance documents and compliance frameworks to ensure consistent application of GDPR, Data Governance Act, and Data Act in agriculture and livestock farming.
Lack of trust among stakeholders and farmers' reluctance to use new technologies and share data (Kaur et al., 2022).	(1) Absence of specific regulations and standards for farm data. (2) The increasing use of AI and other sophisticated tools, potentially leading to breaches of farmers' privacy (Kaur et al., 2022). (3) Limited transparency and control over data collection and processing by technology providers (Kaur et al., 2022). (4) Perceived risks of data misuse and privacy concerns (Grotsch et al., 2025; Krampe et al., 2024; Kaur et al., 2022) and the lack of wide-scale adoption of best practices by technology providers (Kaur et al., 2022)	(1) Develop and enforce sector-specific standards, codes, contracts/ contractual clauses (based on the European Commission's model contractual terms on data access and use[b]) and/or regulations for farm data management, processing, security, sharing and interoperability, in accordance with GDPR, Data Governance Act, and Data Act (also taking into account the CEADS[c]). (2) Increase transparency on data collection, processing and sharing by technology providers. (3) Enable farmers to have more control over data origination from their farms (i.e., give farmers fine-grained control over what data is shared, with whom, and for what specific purpose). (4) Enhance multistakeholder engagement and trust-building.
Lack of clear cybersecurity standards for livestock tracking.	(1) EU cybersecurity law is dispersed across several legal instruments (Mantelero et al., 2021). (2) Connected devices are potentially exposed to cybersecurity threats. This can give third parties the ability to remotely control and exploit on-field sensors. (Gupta et al., 2020).	(1) Develop codes of conduct for cybersecurity in livestock tracking and implement risk assessment protocols.
Low farmer awareness of security best practices.	(1) Human error and lack of training increase vulnerability to breaches (Hazrati et al., 2022).	(1) Provide targeted training programs and awareness campaigns on cybersecurity and data protection.

[a] General Data Protection Regulation.
[b] https://digital-strategy.ec.europa.eu/en/library/draft-recommendation-non-binding-model-contractual-terms-data-access-and-use-and-non-binding.
[c] The Common European Agricultural Data Space.

data. These regulatory complexities may cause a lack of trust among stakeholders and reluctance on the farmers' side to use new technologies and require the establishment of standards and best practices and their adoption by technology providers (Kaur et al., 2022). Considering that the European Commission, on 19 November 2025, published (non-binding and open-to-users' amendments) model contractual terms on data access and use (European Commission, 2025b), preparing standardized contracts (or contractual clauses) for the agricultural (or, more specifically, livestock) data (and technologies) based on these terms and encouraging their sector-wide adoption could play a key role in stipulating rights and obligations of different parties regarding different types of data in a clear way, and ultimately, addressing this lack of trust and the farmers' reluctance to use new technologies.

Finally, the lack of awareness of farmers regarding cybersecurity risks and practices creates real risk for their own business, plants and livestock, and the whole supply chain, and thus the society, in an increasingly digitalized world where there are more and more data points that can be targeted (Hazrati et al., 2022), especially with connected devices being deployed more often (Gupta et al., 2020). This is why it is of utmost importance to raise awareness of farmers on such risks and the strategies to eliminate or mitigate them, in addition to establishing standards and best practices for all the involved stakeholders on cybersecurity (Hazrati et al., 2022).

All these clearly point out the need to develop the context-specific standards, best practices, codes of conduct, and contracts for the stakeholders involved in livestock tracking, mainly including but not limited to farmers and technology providers, on data privacy and (cyber) security, and data governance. Such instruments should assist better implementation of the GDPR rules on data minimization, data security, genuine informed consent, which is even more important in smart environments, like smart farms (Koolen, 2021), and data protection impact assessments, among others. This needs to be done not only according to the GDPR but also the new regulatory developments – primarily, the Data Act and (unless repealed) the Data Governance Act (by providing an approach to address the inconsistencies in these regulations as much as possible) and the agricultural data space.

2.3.5. Gaps and barriers to digital technologies concerning data quality and robustness

When addressing gaps and barriers in digital technologies in livestock farming, the quality and robustness of data play a pivotal role in ensuring effective implementation and decision-making. Data quality refers to the accuracy and reliability of information generated by sensors, IoT systems, and connected tools, which form the backbone of precision livestock farming. Robustness, on the other hand, extends beyond data collection to include the ability of data users to interpret and utilize this information under variable or imperfect conditions. The gaps related to data quality and robustness mainly reflect technical and methodological challenges that influence the reliability of livestock data across the value chain (Table 5). Overall, improving data quality requires coordinated efforts across technology providers, standardization bodies, and end-users.

Data quality remains a critical challenge, as incomplete, inconsistent, and inaccurate data compromise the reliability of analyses and predictive models. Interruptions in data collection caused by sensor failures, connectivity loss, or insufficient battery life often result in incomplete time series, increasing susceptibility to bias. This issue is particularly pronounced in rural areas where GPS and mobile networks are unstable, leading to missing data during key periods (Nicolas et al., 2022). Edge computing offers a potential solution to these connectivity issues in wearable devices, as currently explored within the Horizon OpenAgri Project[4] and, in particular, in the rapidly expanding field of computer vision systems (Benaissa et al., 2025). Environmental factors such as dust, humidity, and temperature fluctuations further introduce noise and inconsistencies into sensor and camera measurements, generating outliers that obscure important signals or trigger false alarms. Unexpected animal behaviors, including unusual movements or interactions, can also disrupt measurements. In addition, the precision and accuracy of data depend on sensor quality and AI algorithms; poorly calibrated sensors or those prone to drift over time produce inaccurate

[4] https://horizon-openagri.eu/.

Table 5
Gaps and barriers in implementing digital technologies in the livestock sector concerning data quality and robustness.

Gaps	Barriers	Solutions
Incomplete data due to sensor failures, connectivity loss, or insufficient battery life (Lebreton et al., 2022; Nicolas et al., 2022)	(1) High costs of advanced, reliable sensors, and adapted IOT networks (Kiefer et al., 2025).	(1) Enhance energy storage, connectivity, and buffer memories. (2) Use redundancy and interoperability for cross-system validation. (3) Broader implementation of edge processing to enable local data storage and pre-processing (Garro et al., 2025)
Inconsistency and noise in the sensor data: environmental factors (dust, humidity, temperature) and unexpected animal behaviors introducing noise or outliers (Schodl et al., 2024; Walker et al., 2024).	(1) High costs of advanced, reliable sensors; lack of proper calibration and maintenance.	(1) Use advanced data preprocessing techniques like Kalman filters, missing data imputation, and smoothing to clean and correct anomalies (Schodl et al., 2024).
Precision and accuracy: poorly calibrated sensors or sensor drift leading to inaccuracies (Gengler, 2019; Tedeschi et al., 2021)	(1) Data analysis strategies affecting data accuracy and precision (statistical vs. machine/ deep learning). (2) Closed system architectures, e.g. black-box models (Gengler, 2019)	(1) Promote regular sensor recalibration and maintenance. (2) Emphasize on-farm validation for robustness under real-world conditions.
Time synchronization and interoperability: lack of temporal synchronization between sensors, leading to inconsistencies in integrated data (Schodl et al., 2024).	(1) Difficulty in aligning multiple sensor outputs; challenges in ensuring seamless interoperability.	(1) Develop standardized protocols for synchronization and encourage interoperability between different systems.
AI data robustness: limited diversity in training datasets causing bias and overfitting (Slob et al., 2021).	(1) High costs and difficulty of collecting diverse, high-quality datasets; (2) over-reliance on volume rather than quality.	(1) Incorporate diverse datasets from different regions, breeds, and conditions; prioritize variance and quality over data volume; foster collaborations to build shared datasets.
Incomplete validation protocols focusing mainly on precision rather than completeness or repeatability (Gómez et al., 2021; Stygar et al., 2021).	(1) Limited on-farm validation and (2) adoption of comprehensive validation protocols.	(1) Encourage on-farm validation under variable conditions; promote adoption of broader validation standards (e.g., completeness, repeatability).
Stakeholder engagement: limited understanding of the impact of data quality among farmers and stakeholders (Yeo and Keske, 2024).	(1) Lack of training and awareness about digital tools and their potential consequences.	(1) Provide training to farmers and stakeholders on the importance of data quality. (2) Promote clear communication and regular equipment maintenance.

measurements that compromise prediction reliability. When multiple sensors operate simultaneously, lack of temporal synchronization and interoperability can lead to inconsistencies in integrated datasets, hindering the ability to analyze interactions between variables effectively.

Several strategies can mitigate these challenges. Technological advances in energy storage, connectivity systems, and buffer memory are essential to reduce data incompleteness, while redundancy and interoperability enable cross-system validation during data cleaning. However, these improvements may increase sensor costs, requiring a balance between reliability and affordability. Robust preprocessing pipelines can detect and correct anomalies using techniques such as Kalman filters, missing data imputation through interpolation or k-NN algorithms, and time-series smoothing. Recent recommendations for data cleaning have emerged for dairy technologies (Schodl et al., 2024) and incorporating expert knowledge into preprocessing further enhances data quality (Do et al., 2024; Van Veen et al., 2025).

Comprehensive validation of digital tools is also necessary, as many solutions lack thorough evaluation (Gómez et al., 2021; Stygar et al., 2021). Existing efforts often focus narrowly on precision rather than completeness or repeatability, making on-farm validation under real-world conditions critical for assessing robustness. Although recommendations for complete sensor validation are available, they require broader adoption (Lloch et al., 2024). Services, such as agrifoodTEF (The European Testing and Experimentation Facilities for Agrifood Innovation)[5] can support the research community in standardizing validation procedures.

Improving data quality also depends on human factors. Engaging farmers and stakeholders in understanding digital tools and the implications of data quality fosters transparency and reduces bias. Clear communication about data usage, combined with regular equipment maintenance such as sensor cleaning and recalibration, ensures more reliable systems. Finally, AI models benefit from training on datasets that capture variability across regions, breeds, environmental conditions, and farming practices. Such diversity reduces bias, mitigates overfitting, and improves adaptability to rare events, such as extreme weather or disease outbreaks. However, creating diverse datasets is costly and complex. Researchers should prioritize variance and quality over sheer volume and foster collaborations to build shared datasets, ensuring broader applicability and reliability of AI-driven solutions.

3. Bridging the digitalization gap in livestock sector: From fragmented solutions to integrated strategies

3.1. Synthesis of key findings

Taken together, this review syntheses digitalization barriers across the livestock value chain, highlighting their interdependencies across technical, economic, socio–organizational, and regulatory domains. Despite significant advancements in digital technologies for livestock production, their integration into livestock value-chain remains a considerable challenge. The main obstacles to digitalization are clustered around issues such as interoperability, economic feasibility, technical competencies, data privacy and security, as well as data quality and robustness. Several of the barriers discussed in this review, including interoperability constraints, data ownership concerns, and lack of common standards, can be traced back to earlier technological choices and fragmented system development (Tedeschi et al., 2021). Overall, the identified solutions point toward several key development pathways for livestock digitalization, including regulatory–driven standardization, the emergence of interoperable data–sharing ecosystems, and increased platform integration across the value chain. These pathways highlight that in order to solve issues related to interoperability, data privacy and security multiple organizations responsible for governance, standardization, and regulatory alignment across the value chain should be involved. Ensuring data quality and robustness primarily calls for targeted actions by technology providers, while overcoming barriers related to technical skills and economic viability demands multi-dimensional approaches involving both primary producers (farmers) and technology vendors. Therefore, to move from conceptual ideas to practical adoption, a strategy that actively involves

[5] https://agrifoodtef.eu/.

stakeholders across the entire value chain is essential.

In the previous chapter, we examined solutions in isolation, focusing on actions relevant to specific topics; here, we adopt a broader perspective to address the problem holistically. Recurring solutions identified across multiple topics are summarized in Table 6. Taken together, the recurring solution categories summarized in Table 6 not only address current barriers but also indicate key directions for future development. Four prominent solutions: training, data governance and standardization, trust building, and collaboration emerged as common recommendations across several analyzed topics. However, those four solutions aiming to bridge the digitalization gap should not be implemented in isolation because they are interdependent and mutually reinforcing.

For instance, without mechanisms that provide verifiable assurance of identity, attributes, and compliance, even well-designed governance frameworks fail, as actors hesitate to share data or adopt new tools (Bernal, 2024; DSSC, 2024). Furthermore, collaboration is essential to align standards across technology providers and producers; otherwise, interoperability remains fragmented, as discussed on the example of ISO working group collaboration presented by Noran (2012).

This review is intended to inform researchers, policymakers and industry stakeholders engaged in development and uptake of digital solutions. By aligning the identified barriers with recent EU data governance initiatives, the review highlights priority areas where coordinated action and targeted interventions are most urgently needed. Several actions supporting these solutions have already been initiated, providing a foundation for further progress. However, it is important to acknowledge certain limitations of this review. Potential selection bias in the reviewed sources, as well as the composition of contributing experts, may have influenced the identification of barriers and gaps, as well as the prioritisation of solutions. Therefore, the results presented in this paper should be interpreted with caution.

3.2. Training and collaboration

Training and collaboration are already being addressed through several EU-level initiatives, which provide a foundation for accelerating digitalization in the livestock sector. The European Innovation Partnership for Agricultural Productivity and Sustainability (EIP-AGRI) serves as a key platform for connecting farmers, researchers, advisors, and agri-business operators, fostering knowledge exchange and multi-stakeholder engagement (https://eu-cap-network.ec.europa.eu/projects_en). In addition to EIP-AGRI, several EU-funded projects such as STEP UP (https://horizon-stepup.eu/) and FARMTOPIA (https://farmtopia.eu/) emphasize training and capacity building, equipping farmers and advisors with digital skills to improve sustainability performance and technology adoption. Similarly, QuantiFarm project (https://quantifarm.eu/) supports the future deployment of digital technology for enhancing sustainability performance. Digi4Live (https://digi4live.eu/) prioritizes data governance and standardization, developing harmonized approaches for data sharing and interoperability across diverse livestock management systems. CEADS (https://ceads.eu/) aims to facilitate data sharing and deploy the Common European Agricultural Data Space. Finally, agrifoodTEF project (https://agrifoodtef.eu/about-agrifoodtef) shows that a strong network supporting further digitalization in livestock production is taking shape. Nevertheless, enhanced coordination between projects is needed to make their impact consistent and long-lasting.

3.3. Building trust in data sharing

Building trust through transparency, certification, and stakeholder confidence is essential for encouraging farmers to share detailed production data. Existing initiatives, such as sustainability programmes using farm-specific life cycle assessment or animal welfare assessment frameworks, demonstrate that farmers are willing to share data when clear value propositions and fair use conditions are established (García Herrero et al., 2025; Stygar et al., 2022; Turland and Slade, 2018). At the sector level, progress remains uneven. The dairy sector, for instance, has advanced more rapidly by embedding data sharing within incentive-based schemes implemented by major companies such as Arla[6] or Valio.[7] These approaches illustrate how financial incentives, combined with institutional credibility, can help operationalise trust and normalize data exchange. In contrast, sectors such as pig and poultry production lag behind, indicating that structural factors, such as supply chain organisation, market concentration, and existing advisory systems, play a critical role in shaping adoption dynamics (Kountios et al., 2025; Massari et al., 2025). Overall, these differences highlight that building trust is not solely a technical or regulatory challenge, but a socio-economic process.

3.4. Data governance and standardization

Data governance and standardization remain critical for creating mechanisms for transparency, certification, and stakeholder confidence. In that respect, new EU-level legislations, most notably the Data Act (European Parliament and Council, 2023) appears, at first glance, to play a pivotal role in narrowing the digitalization gap in the livestock sector by providing a regulatory foundation for guidelines, promoting interoperability, and enabling secure data sharing. The Data Act obliges data holders to make certain types of data accessible to users and third parties under fair, reasonable, and non-discriminatory terms (European Parliament and Council, 2023). However, the devil is in the details. Despite being a substantial step forward, particularly for sectors driven by non-personal data, the Data Act exhibits limitations in agriculture due to its horizontal nature and narrow definitions of certain terms that fall short of adequately addressing agricultural practices. For instance, under the Data Act, the term *user* refers to a natural or legal person who owns or leases a connected product. In practice, technology providers might install sensors, robots, and cameras in barns to collect data while delivering services to farmers without selling or leasing the equipment (Ryan et al., 2024). In such cases, according to the Data Act, the rights over the collected data remain with the equipment owner (e.g., the technology provider).

Furthermore, the Data Act does not cover all data types. Under Chapter II (European Parliament and Council, 2023), companies must share raw and pre-processed data, but they are not obliged to share information derived from such data including derived or inferred insights, as well as highly enriched data (unless otherwise agreed between the user of the connected products or related services and the companies acting as the data holders). For instance, in the case of milking robots, raw sensor readings such as milk temperature, volume, and conductivity, as well as pre-processed data like aggregated milk yield, should be made available. Conversely, algorithm-generated health scores, such as for mastitis detection (e.g. Kamphuis et al., 2010), constitute enriched analytics and remain proprietary, exempt from mandatory sharing. The situation becomes even more complex with accelerometer-based solutions for animal behavioral monitoring. Accelerometers generate continuous three-dimensional movement data (X, Y, Z) and timestamps, which qualify as raw data. That raw data is further processed by algorithms to provide primary behavioral classification (e.g. lying, standing, ruminating) and secondary information used for decision support (e.g. alerts on disease, estrus detection). In many commercially available systems, however, the behavioral classification algorithm is embedded directly in the tag, meaning that raw data (X, Y, Z) are not stored and accessible to data holders, and therefore cannot be shared. Behavioral

[6] https://foodnationdenmark.com/cases/incentive-scheme-aims-to-speed-up-climate-action/.

[7] https://www.valio.fi/vastuullisuus/elainten-hyvinvointi/maksamme-vastuullisuuslisaa-tuottajille/.

Table 6
Summary of recurring solution categories across identified topics and their contribution to addressing key challenges.

Solutions	Topics				
	Interoperability	Economic viability	Technical skills	Data privacy & security	Data quality & robustness
Training[a]		✓	✓	✓	✓
Data governance and standardization[b]	✓			✓	✓
Trust building[c]			✓	✓	✓
Collaboration[d]	✓	✓		✓	✓

[a] Building technical skills and awareness among stakeholders.
[b] Establishing rules, protocols, and standards for data handling.
[c] Creating mechanisms for transparency, certification, and stakeholder confidence.
[d] Promoting multi-stakeholder engagement, participatory design, and cooperative models.

classifications such as lying, standing, walking, or rumination are not raw sensor signals, but it is unclear whether they should be treated as "data which have been pre-processed for the purpose of making them understandable and useable prior to subsequent processing", which fall within the scope of the Data Act, or insights derived from data (as the "outcome of additional investments into assigning values or insights from the data, in particular by means of proprietary, complex algorithms, including those that are a part of proprietary software"), which fall outside the scope of the Data Act. For practical applications, such as animal welfare certification or improved breeding programs, farmers would benefit from accessing the animal behavioral information. If such access is denied and farmers request raw data instead, sensor companies, even if the data is accessible to them as data holders, may face challenges due to, for instance, the sheer data volume. The Data Act, starting from 12 September 2026, requires that connected products and related services, *where relevant and technically feasible,* should be designed so that users can directly access data generated by their use. However, the interpretation of "relevant" and "technically feasible" remains uncertain. Where data cannot be directly accessed by the user, those companies must make the readily available data and relevant metadata necessary to interpret and use those data, accessible to the user. Although the Data Act provides a definition to "readily available data" as "product data and related service data that a data holder lawfully obtains or can lawfully obtain from the connected product or related service, without disproportionate effort going beyond a simple operation", this definition is also open to interpretation, in particular the part "without disproportionate effort going beyond a simple operation". Consequently, animal behavioral monitoring data may ultimately remain, at least to some extent, inaccessible, hindering its use for purposes such as animal welfare certification (as discussed by Stygar et al., 2023) or breeding purposes (Brito et al., 2025). While the Data Act provides mechanisms for dispute resolution through settlement bodies or national competent authorities (European Parliament and Council, 2023), these uncertainties may ultimately result in legal challenges and even court cases to clarify obligations and set precedents. Such rulings could significantly influence industry practices, particularly regarding what constitutes "readily available" data and the criteria for relevance and technical feasibility. In the meantime, farmers and innovative small businesses have a strong incentive to negotiate data access proactively, using the current regulatory momentum to secure more favorable terms and reduce future dependency on technology providers.

In practice, however, the Data Act does not fully resolve the problem of data lock-in (Ryan et al., 2024), which manifests as limited or non-existent farmer control over data once collected by the initial technology providers, and significant barriers to switching providers (including prohibitive costs or technical incompatibility) (Atik and Martens, 2021). This is because the horizontal nature of the Data Act and the narrow definitions of "product", "related service" and "user" does not sufficiently consider the particularities of the agricultural sector, and, thus, fall short of addressing this problem.[8] Two underlying issues are the absence of interoperability and data standards and the absence of clearly enforceable rights over farm data sets, which are often non-personal data falling out of the scope of the data subject rights under the GDPR (Ryan et al., 2024).

3.5. Future directions

Among the identified solutions, improving access to sensor data and establishing clear, enforceable data-sharing frameworks emerge as the most critical and actionable priorities in the short term. We postulate that the lack of access to sensor data is a key barrier for successful data sharing in the livestock sector. Therefore, industry associations should continue efforts to showcase successful partnerships and new business opportunities in order to encourage companies to provide public API's and access to relevant data with consent from farmers. To strengthen interoperability and trust among stakeholders, the EU Code of Conduct on Agricultural Data Sharing by Contractual Agreement (COPA-COGECA, 2018), should be updated and aligned with the Data Act, by addressing the practices in the sector. Therefore, we strongly support the recommendations proposed by Ryan et al. (2024), concerning extending the Code with practical examples, model contracts, GDPR guidance, as well as enforcement frameworks. We recommend drafting livestock sector-specific model contracts (or contractual clauses) based on European Commission's model contractual terms on data access and use, in a way addressing the issues explained above, in particular the gaps left by the Data Act in the context of livestock tracking (and, more generally, agriculture), clarifying the roles, obligations and key terms in this context and, by doing so, mitigating the data lock-ins and other sector specific issues, and establish clearly enforceable rights and ensure greater control for the users over the data originating from their farm operations. This will likely contribute to building trust and accelerating adoption of digital solutions across the livestock sector.

4. Conclusions

Progress in digital livestock technologies has been substantial, but their adoption and integration throughout the value chain remains challenging. Our review highlights digitalization obstacles related to interoperability, economic viability, technical skills, data privacy and security, and data robustness and quality. Overall, addressing these issues requires coordinated efforts; governance and standardization bodies must tackle interoperability and privacy concerns, technology

[8] It is noteworthy that the European Commission's model contractual terms on data access and use provide useful information regarding access rights of the parties in relation to a transfer of use and multiple users, in the example case of connected agricultural machinery rented out by an initial user to subsequent users.

providers should ensure data quality and robustness, and multi-dimensional strategies involving farmers and vendors are needed to overcome technical skill and cost barriers. Integrating fair profit–sharing business models can further strengthen farmers' incentives to adopt new digital solutions and engage actively in data–driven value creation. The Data Act provides a regulatory foundation for data sharing, but its limitations, such as its horizontal nature, narrow or unclear definitions and exclusion of derived insights, leave critical gaps, potentially leading to legal disputes and court cases that will shape future interpretations. In practice, data lock-in persists as a major barrier, underscoring the need for proactive negotiation, public APIs, and stronger industry collaboration. Updating the EU Code of Conduct and aligning it with the Data Act and drafting livestock sector-specific model contracts (based on the European Commission's model contractual terms for data access and use) and encouraging its sector-wide use will be essential for building trust, ensuring transparency, and accelerating practical adoption of digital solutions across the livestock sector.

CRediT authorship contribution statement

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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