# SECTION E: TECHNOLOGY

## 1. Introduction

This chapter presents an analysis of the state of the art and current capacities related to the use of reproductive, molecular and information and communication technologies (ICT). In *the Second Report on The State of the World's Animal Genetic Resources for Food and Agriculture* (SoW-AnGR; FAO, 2015), the dedicated section concluded that, despite some progress since the first report, major gaps persisted in both the availability and practical application of these technologies. Most countries reported use of little beyond Artificial Insemination, with many other reproductive biotechnologies remaining confined to experimental settings, and adoption constrained by technical limitations, inadequate funding and infrastructure, shortages of trained personnel, and various organizational or socio-ethical barriers, particularly in developing regions. Although a wider range of stakeholders, including an expanding private sector, had become involved, the report emphasized the need for carefully planned deployment of these powerful tools within robust AnGR management frameworks to ensure that productivity gains do not compromise genetic diversity or long-term sustainability. While the growing importance of information systems and digital tools was acknowledged, the topic was addressed only to a limited and supporting extent, and ICT related questions were not integrated in the 2025 SoW-AnGR reporting process.

This section reviews the current state of knowledge on reproductive and molecular biotechnologies, as well as ICT relevant to the management of animal genetic resources, drawing on recent scientific literature. It then uses information provided in the 2025 country reports to assess the state of capacity and actual use of these technologies at national level. The analysis provides a global overview of adoption patterns, examines stakeholder involvement, and reviews ongoing research activities, while noting developments and constraints relative to the second SoW-AnGR.

# 2. State of the art

## 2.1. Reproductive technologies

Reproductive biotechnologies, also collectively referred to as assisted reproductive technologies (ARTs), provide a practical toolbox for managing animal genetic resources, supporting both breeding and conservation activities, for instance through the establishment of gene bank collections and the future use of stored material to restore or reinforce populations. Across livestock species, most ARTs can achieve these objectives, but outcomes vary widely due to differences in species and breed biology, individual animal variation, and the quality of procedures for collection, processing, storage and use. A realistic assessment of efficacy is therefore essential: “success” is not only a function of the technology itself, but also of implementation and quality management.

Among available ARTs, artificial insemination (AI)[1] remains the most widely applied and operationally mature across livestock species. AI can be implemented using different deposition techniques adapted to species anatomy and management conditions (e.g. laparoscopic, cervical, vaginal or intrauterine approaches, including deep intrauterine methods when appropriate). In small ruminants, the choice of technique is often linked to semen status (fresh, cooled or frozen–thawed), with laparoscopic insemination frequently associated with frozen semen. However, acceptable fertility outcomes have also been reported with non-surgical approaches under appropriate conditions and good management. The insemination techniques are well established, and likewise the semen collection and cryopreservation protocols, with sperm fertility resulting from the use of these ARTs often exceeding 50% regardless of species (cattle, sheep, goat, boar, chickens), although the results are highly variable. Rectifying and understanding that variability has drawn significant attention, consequently resulting in a refocusing on quality control (Althouse, 2024; Brito, 2024; Pezo *et al.*, 2024; Rodriguez-Martinez *et al.*, 2024; Waberski & Luther, 2024), improving semen cryopreservation diluents (Bodu et al., 2025, cattle, ram, rooster), proteomics or biomarkers (Llavanera, 2024, Tirpak *et al.*, 2024), and the use of combinations of technologies like computer assisted semen analysis and genetic predictors (Azevedo *et al.*, 2024) or various semen sexing technologies and AI or MOET (Kumar *et al.,* 2024). In addition to ejaculated semen, epididymal sperm can be recovered from the testes/epididymides and cryopreserved, notably when a valuable male dies unexpectedly or cannot be collected using standard methods (Box 2E1). Across these developments, the overarching goal is to increase the functional predictability of semen quality and thereby improve fertility and consistency under field conditions.

**Box 2E1. Successful use of epididymal sperm in the conservation of native breeds**

For the first time in Finland and in the Nordic countries, calves have been born following artificial insemination of cows using epididymal sperm collected from a slaughtered bull. Two Eastern Finncattle bull calves were born in 2025 at the Kainuu Vocational College herd in Kajaani, Finland—a herd that serves as a living gene bank for this rare breed. Moreover, one female calf was born on a private farm and the epididymal sperm was successfully used for laboratory embryo production. Currently, epididymal sperm has been cryopreserved from three native cattle breeds and from the Finnhorse, Finnsheep, Finngoat, Finnish Landrace chicken roosters, and semi-domesticated reindeer.

Finland is one of the first countries internationally to have launched a national strategy for the conservation of animal genetic resources. The first national actions were taken in 1984 to safeguard the genetic diversity of domestic animals. The current activities in Finland are based on the National Genetic

[1] In this chapter, the abbreviation “AI” refers exclusively to Artificial Insemination. The term artificial intelligence is written in full and is not abbreviated.

Resources Programme for Agriculture, Forestry and Fisheries, published in 2018 by the Ministry of Agriculture and Forestry and coordinated by the Natural Resources Institute Finland.

In the Finnish National Program, living gene bank herds have been established for the native cattle and sheep breeds. These living gene banks are maintained at Ahlman, Kainuu and Lappia Vocational Colleges. Cryopreservation of semen and preimplantation stage embryos were the first in vitro conservation measures to complement in vivo conservation of animal genetic resources. Ejaculated semen is cryopreserved at artificial insemination (AI) stations. Now, artificial insemination using epididymal sperm has been allowed through an amendment by the Ministry of Agriculture and Forestry. Moreover, the Natural Resources Institute Finland has the registered collection and cryopreservation facility for epididymal sperm for domestic use.

Epididymal sperm and ejaculated semen complement each other in conservation measures. The required infrastructure for collection of epididymal sperm is inexpensive compared to that of ejaculated semen but only one collection is possible instead of repeated collections at AI stations. Collection of epididymal sperm offers a novel and cost-effective approach to increase the number of breeding males in native breeds, to manage inbreeding and effective population sizes of the breeds, and to preserve genetic diversity.


*Epididymal bull sperm in gene bank and Finncattle calf born from epididymal bull sperm insemination*
*Photo credit: Tuula-Marjatta Hamama, Marjut Vertanen*

*Provided by Juha Kantanen, Jaana Peippo and Heli Lindeberg.*

Perhaps an area of research drawing the greatest amount of attention is that of hormonal control of estrus (i.e., heat or a female's receptivity to a male), estrous (the entire cycle), and the timing of ovulation, particularly with small ruminants (Souza-Fabjan *et al.*, 2023). Improved control of estrus and ovulation enhances AI outcomes by enabling better timing of insemination relative to ovulation. It also supports embryo technologies by increasing the number of oocytes available following induced ovulation and improving the quantity and quality of embryos produced for transfer, thereby increasing the number of live offspring obtained (Lucy & Pohler, 2025; Pascottini *et al.*, 2025).

Embryo transfer (ET) technologies provide a second major pathway for rapid multiplication and targeted use of genetic resources. Traditional embryo collection and transfer methods have been widely implemented in several species, and their integration with superovulation protocols supports the production of multiple embryos from genetically valuable females. In small ruminants, non-surgical embryo recovery (NSER) has attracted renewed attention as an approach that can reduce invasiveness and facilitate wider use. Progress has been linked to improved cervical management, including the use of cervical dilators and hormonal protocols that facilitate cervical penetration (Gonçalves, 2024). Reported results indicate high rates of cervical access and embryo recovery under suitable conditions, with application in both sheep and goats. However, species differences remain important: outcomes in goats may approach those obtained by surgical methods, whereas in sheep laparotomy has often remained the principal option due to differences in cervical structure and dilation potential. Where feasible, NSER can increase the efficiency of embryo collection for gene banking and enable more frequent or more practical recovery, thereby supporting the accumulation and utilization of germplasm resources.

While the previous descriptions of oocyte collection, fertilization, and embryo production and transfer focused on in vivo techniques, in vitro fertilization and subsequent embryo transfer are still viable ARTs and are widely used across species. Moreover, the utility of a single straw of frozen-thawed bull semen, for example, can increase significantly when used to fertilize large numbers of oocytes, potentially resulting in the production of dozens of offspring from a single round of IVF. Furthermore, embryos produced from these ARTs can likewise be used for transfer resulting in success rates similar to AI for cattle (Hansen, 2023), but less so with pigs (Garcia-Canovas *et al.*, 2024) or frozen (cryopreservation or vitrification) for preservation of genetic resources.

Possibly the most rapidly evolving area of ART development is that of cloning of mammalian species and genetic engineering. Moreover, coupling the two ARTs can often result in powerful tools capable of producing animals with enhanced disease resistance and selection for specific production traits, among other applications (Skrzyszowska & Samiec, 2021). On their own, cloning can be used for a variety of purposes such as fertility preservation and repopulation (Skrzyszowska & Samiec, 2021) and the genetic resources necessary (tissue samples) can be easily collected, frozen, thawed and cultured (Purdy *et al.*, 2025). Frozen semen can then be used in subsequent generations to broaden the genetic diversity of the cloned offspring. However, the genetic engineering aspects of ARTs, valuable tools for improving animal productivity, can be used for a variety of purposes such as environmental adaptation (slick gene in cattle), transgenic production or biomedical models (Skrzyszowska & Samiec, 2021).

Poultry, because of their different anatomies and gametes face challenges that mammalian species do not experience. For example, while mammalian oocytes and embryos can be cryopreserved or vitrified this is not possible with poultry because of the structure of the germplasm. Consequently, alternatives for germplasm preservation and use have been developed and include gonad collection, vitrification, and transplantation from newly hatched chicks and poults. These techniques have low success rates compared to many other ARTs but do offer the possibility for preservation and rejuvenation of populations. Similarly, the use of primordial germ cells (PGC, Hu *et al.*, 2022) permits the collection and use of chicken genetic resources (ducks, geese, quail, and turkey methods are currently being explored) but with a higher success rate compared to the gonad collection and transplantation methods. Moreover, the PGC methods are simpler than the gonad methods and are performed embryonically which can be substantially scaled up.

Taken individually, the main ARTs provide workable options for preserving genetic resources and supporting population recovery when needed. Importantly, when ARTs are combined (e.g. artificial insemination with superovulation, or MOET with IVF) a synergistic effect can occur, increasing the number of offspring produced per unit of conserved germplasm and improving the overall efficiency of conservation and breeding programmes. In gene banking contexts, integrated use of semen and embryos can also strengthen risk management by diversifying the types of stored material and expanding options for reconstitution across varying operational constraints.

## 2.2. Molecular biotechnologies

Over the past decade, the most notable advances in molecular biotechnologies have been the progressive integration of genomics into characterization (crossreference to the chapter on characterization), breeding programmes (crossreference to the chapter on breeding) and, to a more limited extent, conservation activities (crossreference to the chapter on conservation). While the major livestock species had already been sequenced by the time the second SoW-AnGR was prepared, the quality and completeness of reference genomes and associated resources have improved markedly, strengthening downstream applications in breeding and management (Georges *et al.*, 2019). At the same time, the use of microsatellites has continued to decline in many applications, as SNP genotyping and wholegenome sequencing (WGS) have become the dominant platforms for highresolution characterization and genetic analyses (Mészáros et al., 2026) (cross reference to thematic study on genetic variation).

A growing number of functional and adaptive markers and quantitative trait loci (QTLs) have been identified and progressively integrated into markerassisted selection schemes (Hassanine *et al.*, 2025). Genomic selection, initially developed and widely adopted in dairy cattle, has subsequently expanded to other major livestock species (box 2E2; however, its broader implementation remains constrained by the availability of sufficiently large, well-characterized reference populations (Jinya, 2024). Estimates of the impact of genomic selection indicate increases in genetic gain ranging from approximately 20 percent in broiler chickens to up to 120 percent in dairy cattle, accompanied in the latter by a reduction of the generation interval of around two years (Chakraborty *et al.*, 2022). In parallel, methodological developments have enabled the application of genomic selection in crossbreeding systems (Mei et al., 2023) and the implementation of multibreed genomic prediction approaches (Clasen *et al.*, 2023).



**Box 2E2. Gradual adoption of advanced genomic selection methodologies in dairy cattle breeding in India**

---

Over the past decade, India has progressively moved from conventional progeny testing towards the use of genomic information in dairy cattle breeding programmes, reflecting both the scale of its dairy sector and the predominance of smallholder production systems. Initial efforts relied on pedigree- and phenotype-based evaluations, but limitations related to long generation intervals and incomplete recording stimulated interest in genomic approaches capable of delivering earlier and more accurate selection decisions.

The first phase of adoption focused on the creation of national reference populations and species- and breed-adapted SNP chips, supported by coordinated recording programmes for indigenous breeds and crossbreds. These developments enabled the application of genomic best linear unbiased prediction (GBLUP) for the estimation of genomic breeding values in several dairy breeds. Subsequently, the availability of both pedigree and genomic data facilitated the transition towards single-step GBLUP (ssGBLUP), which integrates all sources of information within a unified evaluation framework and is better suited to Indian conditions, where pedigrees are often incomplete but phenotypic data are abundant.

Recent studies using large field datasets have demonstrated that ssGBLUP provides more accurate and less biased breeding value estimates than traditional or genomic-only models, particularly for milk yield traits in crossbred cattle managed under smallholder systems (Nayee, 2018; Khan *et al.*, 2025). In parallel, national initiatives led by ICAR and NDDB have initiated routine genomic evaluation of young bulls, notably for indigenous dairy breeds such as Sahiwal, with genomically evaluated semen increasingly entering artificial insemination programmes (ICAR, 2026).

Overall, the Indian experience illustrates a gradual, pragmatic transition towards advanced genomic selection methodologies, characterized by incremental capacity building, adaptation of models to local data structures and progressive integration into operational breeding programmes, rather than abrupt replacement of conventional approaches.

---

Beyond genomics, there has been growing interest in other "omics" approaches, such as transcriptomics, proteomics, metabolomics and epigenomics, which can help link molecular mechanisms to traits of relevance for breeding, reproduction and health management (Wadood *et al.*, 2025). In dairy cattle, transcriptomic studies have identified genes and pathways associated with milk protein synthesis, lipid and carbohydrate metabolism, and immune and inflammatory responses, illustrating how gene expression profiles can inform understanding of complex production and resilience traits (Zhou et al., 2019). Similarly, increasing attention is being given to noncoding RNAs as regulators of economically important traits, with recent work highlighting their roles in regulatory networks underpinning traits such as fat deposition and related aspects of product quality (Yang *et al.*, 2023). In parallel, advances in singlecell and multiomics approaches are improving understanding of early embryonic development by resolving cellular heterogeneity and identifying pathways associated with developmental competence and embryo arrest, with implications for refining assisted reproductive technologies (e.g. IVF and ET) (Zhang *et al.*, 2024). A practical example of applied omics is the use of semen proteomics in artificial insemination programmes to identify sperm proteins associated with field fertility in AI bulls, supporting the development of biomarker panels that can improve the screening and ranking of breeding males beyond conventional semen quality tests (Rabaglino *et al.*, 2022). However, integrating omics into routine livestock biotechnology and AnGR management remains challenging. Key constraints include the volume and complexity of omics datasets, the need for robust and interoperable bioinformatics pipelines for analysis and integration, and persistent gaps in high quality phenomic data and specialized expertise required to translate molecular signals into operational decision support tools (Wadood *et al.*, 2025).

Genome editing technologies, such as CRISPR-Cas systems, as well as base and prime editing, have advanced rapidly and offer potential applications for enhancing disease resistance and environmental adaptation (cross-reference to the chapter on gene editing). These tools are increasingly being explored to introduce traits related to disease resistance, polledness, improved productivity, and tolerance to environmental stressors (Wang *et al.*, 2025). Gene-editing approaches have, for example, been used to induce targeted mutations in myostatin and other muscle-related genes, resulting in increased muscle growth and improved feed efficiency in several livestock species (Zhao *et al.*, 2022). Despite these advances, the adoption of gene-edited animals and products remains constrained by regulatory uncertainty and variable levels of public acceptance across regions.

Beyond direct breeding applications, recent developments in molecular biotechnologies are also increasingly influencing animal genetic resources management indirectly, notably by strengthening capacities for disease surveillance, prevention and response. High-throughput molecular diagnostics, including PCRbased assays, metagenomics and multiomics approaches, enable rapid detection and characterization of pathogens, thereby supporting earlywarning systems, targeted control measures and improved protection of genetically diverse livestock populations. In parallel, the development of next generation vaccines, such as recombinant, vector-based and mRNA platforms, facilitates more precise and adaptable disease control strategies, contributing to the long-term sustainability, resilience and safe use of animal genetic resources across production systems (Marzouk & Alajaji, 2025).

Taken together, recent developments in molecular technologies highlight two key messages. First, their development and adoption remain uneven across species, regions and production systems, reflecting differences in investment, infrastructure and institutional capacity. Second, much of the progress achieved in molecular biotechnologies has been enabled by parallel advances in big data analytics and information and communication technologies, which underpin data generation, integration and interpretation, as discussed in the following section.

## 2.3. Information and communication technologies

Information and communication technologies comprise a broad set of tools and services that support the access, retrieval, storage, transmission and manipulation of information in digital form, including the internet, wireless networks, computers, software and related communication applications (FAO, 2026). ICTs are increasingly embedded in livestock systems through connected devices and platforms that enable continuous or frequent data capture, integration and analysis, thereby supporting more timely management decisions across production, health, welfare and value-chain functions (Akhigbe *et al.*, 2021; Neethirajan & Kemp, 2021). These developments underpin precision livestock farming, which applies ICTenabled monitoring, sensing and data analytics to manage livestock systems at the level of individual animals or groups in a systematic and data-driven manner, and is currently implemented mainly in intensive and semi intensive production systems, where high levels of automation and controlled conditions facilitate continuous data collection (Akhigbe *et al.*, 2021; Brito *et al.*, 2025 ; Neethirajan & Kemp, 2021). There are, however, applications available to other production systems, as well as to the broader environment involved in the conservation and use of animal genetic resources.

Modern ICT applications in livestock production are typically organized around layered digital architectures. These generally include physical, network, edge, and cloud layers, which together support the collection, transmission, processing, and analysis of data (Akhigbe et al., 2021). The physical layer consists of sensors attached to animals or equipment that collect biological, behavioural and environmental data. The network layer provides connectivity, enabling data transfer through wired or wireless communication infrastructures. The edge layer supports local data processing close to the data source, while the cloud layer provides centralized computing capacity, data storage, and advanced analytics. The cloud layer increasingly hosts large databases and analytical tools, including capabilities for data visualization, machine learning and Artificial Intelligence. The edge and cloud components together enable the integration of data streams originating from multiple sources, such as animals, housing environments and farm equipment. This architecture forms the basis of many ICT-enabled livestock applications, including precision livestock farming systems and automated decision support tools (Akhigbe et al., 2021). Beyond technical connectivity, effective integration also depends on semantic interoperability, including standardized terminology and structured data models, which are increasingly recognized as important in livestock health management and disease surveillance systems (Noor et al., 2026).

Sensors represent one of the most visible and rapidly expanding components of ICT use in livestock systems. Depending on their purpose, sensors may be wearable or implanted, and are capable of recording parameters such as body temperature, activity, heart rate, respiration rate, rumen pH, spatial location and behavioural indicators (crossreference to the chapter on phenotype). External sensors including video cameras, microphones, thermal infrared cameras and load cells complement onanimal devices, while environmental sensors monitor temperature, humidity, air quality and other housing conditions (Neethirajan & Kemp, 2021). In dairy systems, sensors integrated into milking equipment routinely record milk yield, flow rate, composition, electrical conductivity and somatic cell count, providing continuous phenotypic information. In most practical contexts, sensor systems are deployed in combination, allowing multiple parameters to be captured simultaneously. This integrated approach enhances the robustness of livestock monitoring and supports more comprehensive management objectives, including breeding, feeding and health management. Beyond the challenges of applying these technologies in extensive systems, their integration into national and international breeding programmes remains limited by fragmentation, lack of standardization, and constraints related to data access, interoperability and governance; recent reviews have therefore emphasized the need for coordinated data infrastructures, transparent data-sharing arrangements and agreed standards for the effective use of sensor-derived phenotypes in breeding and genetic evaluation (Brito *et al.*, 2025).

Automation is another major dimension of ICT adoption in livestock production. Rising labour costs, constraints on skilled labour availability and improvements in the affordability and reliability of automated equipment have resulted in increased uptake of systems for milking, feeding, animal handling, weighing, body condition scoring and climate control. These systems not only reduce labour requirements but also generate large volumes of standardized data, which are essential for managing large herds or flocks effectively (Akhigbe *et al.*, 2021). Automated data capture improves consistency and reduces human error in routine measurements, thereby strengthening the quality of information available for management and breeding decisions. The availability of such data is particularly relevant for animal genetic resources management, where reliable identification and long-term monitoring of populations are fundamental prerequisites for both conservation and improvement programmes.

Decision support systems constitute a key interface between data collection and practical livestock management. These systems integrate data from sensors, farm equipment and external sources to generate information that supports management decisions relating to breeding, feeding, herd organization and disease control. Computerization of these processes increases the speed and consistency of decisionmaking and reduces subjective bias. As emphasized in several reviews, the integration of ICTs supports a gradual transition in livestock management strategies from reactive approaches, towards proactive and predictive ones, in which historical and realtime data are used to anticipate future needs or risks (Akhigbe *et al.*, 2021; Neethirajan & Kemp, 2021). For animal genetic resources, such systems can contribute to the early detection of declining trends in population size or performance and facilitate timely management responses.

Beyond farm-level management, ICTs play a crucial role in information dissemination and advisory services. The expansion of mobile network coverage, combined with the widespread availability of lowcost smartphones and mobile internet services, has made mobile applications a primary channel for communication with livestock keepers, replacing earlier tools such as information kiosks or static digital media (FAO, 2017; Box 2E3). Mobile-based platforms allow the dissemination of technical guidance through multilingual text, audio and video content, and support rapid updates and notifications. They also provide channels for sharing information on animal health risks, extreme weather events, emerging diseases and vaccination campaigns. In addition, access to market information and digital trading platforms for livestock, livestock products and inputs can improve economic outcomes for producers by reducing transaction costs and intermediaries (FAO, 2017).

**Box 2E3. Digital tools for monitoring animal breeding and genetic management by smallholders**

Digital livestock tools are increasingly promoted as enablers of improved livestock management and rural development in low-income countries, including contexts dominated by smallholder and pastoral production systems. Beyond their role in advisory services and production optimisation, such tools hold growing potential for supporting the management, breeding and characterization of animal genetic resources (AnGR) by small producers.

Examples from Kenya and India highlight both the opportunities and the limitations of digital livestock tools in practice (Daum *et al.*, 2022). Most of these tools can be characterized as “simple” or “smart” digital applications, typically smartphone-based, which rely primarily on manually entered data rather than on automated sensors. Applications such as iCow in Kenya, which are estimated to have had approximately 50 000–60 000 active users (STEM Prize, 2021), demonstrate how digital platforms can facilitate the recording of basic animal information, such as age, reproductive events and health observations, while supporting cattle pregnancy monitoring and strengthening linkages between farmers, extension agents and service providers. In India, the Herdman application, which primarily targets veterinary and extension services employed by dairy cooperatives and dairy processors reaches tens of thousands of farmers indirectly, improving their access to artificial insemination and veterinary services and facilitating the collection of data for a more systematic implementation of breeding programmes.

When deployed through cooperatives or producer organisations, such tools can contribute to improved documentation of livestock populations and, potentially, to better monitoring of breed performance under local conditions.

However, the study also highlights significant challenges and constraints. Access to smartphones, connectivity, digital literacy and sustained organisational support remain uneven, shaping who benefits from digital tools and how. More advanced “smart and connected” technologies based on sensors are rarely accessible to small producers, while concerns related to data ownership, data sovereignty and power asymmetries between farmers, service providers and platform developers are increasingly prominent. Moreover, most tools focus on dairy cattle, with limited attention to other species or to pastoral and extensive systems where locally adapted breeds play a central role.

Overall, the case of Kenya and India illustrates that digital livestock tools are not a silver bullet for AnGR management by small producers. Their potential to support the characterization, monitoring and sustainable use of animal genetic resources depends critically on context-specific design, inclusive governance arrangements and integration within broader institutional frameworks

---

The increasing use of sensors and automated systems has resulted in very large and complex datasets, the effective use of which requires advanced analytical approaches. Big data analytics and Artificial Intelligence techniques, including machine learning, are therefore becoming integral components of modern ICTenabled livestock systems. These tools enable the identification of patterns, trends and anomalies in highvolume datasets and reduce reliance on manual data analysis (Neethirajan & Kemp, 2021). The two main fields of application of artificial intelligence to animal breeding relates broadly to phenotype generation and predictive genetic modelling. While Artificial Intelligence and machine learning technologies are increasingly used for generating phenotypes, especially considering image and sensor data, artificial intelligence models do not necessarily outperform linear models, and the application of artificial intelligence to tabular data is still posing significant challenges in the context of genomic prediction (Morota *et al.*, 2026). Also many of these applications remain under development and that issues related to data quality, model validation, transparency, integration, and practical deployment architectures must be addressed before widespread deployment at scale (Neethirajan & Kemp, 2021; Morota et al., 2026; Guo et al., 2025).

Blockchain technologies are also being explored within livestock value chains, primarily to enhance traceability, transparency, and data integrity. Potential applications include certification processes, automated transactions, and secure recording of animal movements and product histories from farm to market. Blockchain enables decentralized and immutable data storage, thereby increasing trust among breeding organizations, producers and other stakeholders, facilitating data exchange across institutions, and improving traceability along breeding and production chains (Yang *et al.*, 2025).While promising, these technologies remain at an early stage of adoption in most livestock systems and require further evaluation in diverse production contexts (Neethirajan & Kemp, 2021).

Collectively, ICTs and Artificial Intelligence offer significant opportunities for improving the management of animal genetic resources by strengthening identification systems, enhancing data quality, and supporting more systematic monitoring of populations, performance and management practices. At the same time, their effective use depends on enabling conditions, including appropriate infrastructure, institutional arrangements, data governance frameworks, and capacity development. At the global level, systems such as the FAO Domestic Animal Diversity Information System (DAD-IS) illustrate how digital information systems can support the monitoring of national breed populations and more informed decision-making on animal genetic resources. Reviews consistently note that barriers such as connectivity limitations, energy requirements, technical complexity and skills gaps may constrain adoption, particularly in small-scale and extensive systems (Akhigbe *et al.*, 2021). In addition, inconsistencies across livestock population datasets can complicate trend analysis and downstream policy use unless data are carefully validated and reconciled (McKechnie et al., 2025). For animal genetic resources management, it is therefore essential that ICT strategies are aligned with local realities and that digital tools complement, rather than replace, established institutional processes for breeding, conservation and stakeholder engagement.

# 3. Global overview of capacities on reproductive and molecular biotechnologies

Similarly to the second report, countries were requested to report to what extent various molecular and reproductive biotechnologies are used, on the basis of the list below (see the *Second Report on the State of the World's Animal Genetic Resources*, (FAO, 2015) for detailed descriptions):

1. Artificial insemination (AI)
2. Embryo transfer (ET)
3. Multiple ovulation and embryo transfer (MOET)
4. Semen sexing
5. In vitro fertilization
6. Cloning
7. Genetic engineering
8. Molecular genetic or genomic information
9. Transplantation of gonadal tissue

The country-report questionnaire requested countries to indicate the level of availability by providing a score (by species): none; low (at experimental level only); medium (available to livestock keepers in some locations or production systems); or high (widely available to livestock keepers). The responses by region are summarized by in Tables 3E1 and 3E2, regarding the use of the technologies (score from low to high for at least one of the big five species).

Artificial insemination remains by far the most widely used biotechnology, with 96 percent of reporting countries indicating at least some level of use. In all regions except the Southwest Pacific, more than 90 percent of countries reported using AI. ET, the use of molecular genetic and genomic information, and multiple ovulation and embryo transfer (MOET) are less widely applied, but still reported by 68, 59, and 58 percent of countries, respectively. More than 80 percent of countries in Europe and North

America reported using all three of these technologies. In Asia and Latin America and the Caribbean, similar proportions of countries reported using ET and MOET, but fewer than half indicated the use of molecular genetic and genomic information. Interestingly, 55 percent of Near East countries reported using molecular genetic and genomic information, while only a minority reported applying ET (27 percent) or MOET (9 percent).

**Table 3E1. Use of reproductive and molecular biotechnologies – regional breakdown**

| Regions | Number of countries | Artificial insemination (%) | Embryo transfer (%) | Molecular genetic or genomic information (%) | Multiple ovulation and embryo transfer (%) |
|---|---|---|---|---|---|
| Africa | 35 | 94 | 43 | 40 | 29 |
| Asia | 14 | 100 | 93 | 50 | 86 |
| Southwest Pacific | 2 | 50 | 0 | 0 | 0 |
| Europe | 31 | 100 | 94 | 94 | 84 |
| Latin America and the Caribbean | 17 | 94 | 82 | 47 | 82 |
| Near East | 11 | 91 | 27 | 55 | 9 |
| North America | 2 | 100 | 100 | 100 | 100 |
| World | 112 | 96 | 68 | 59 | 58 |

*Notes: Figures indicate the proportion of countries reporting the use of specific biotechnologies for any of the big five species.*
*Source: Country reports, 2025.*

Regarding more advanced reproductive and molecular biotechnologies, semen sexing and in vitro fertilization were moderately widely used, reported by 54 and 42 percent of countries, respectively. Their use was concentrated mainly in North America, Europe, Latin America and the Caribbean, and Asia. In contrast, only 14 percent, 12 percent, and 11 percent of countries reported using genetic engineering, cloning, and transplantation of gonadal tissue. Notably, however, 50 percent of countries in North America and 43 percent in Asia reported the use of cloning.

**Table 3E2. Use of advanced reproductive and molecular biotechnologies – regional breakdown**

| Regions | Number of countries | Cloning (%) | Genetic engineering (%) | In vitro fertilization (%) | Semen sexing (%) | Transplantation of gonadal tissue (%) |
|---|---|---|---|---|---|---|
| Africa | 35 | 3 | 6 | 6 | 29 | 9 |
| Asia | 14 | 43 | 29 | 50 | 64 | 14 |
| South west Pacific | 2 | 0 | 0 | 0 | 0 | 0 |
| Europe | 31 | 6 | 10 | 71 | 84 | 13 |
| Latin America and the Caribbean | 17 | 12 | 24 | 71 | 76 | 12 |
| Near East | 11 | 9 | 18 | 18 | 0 | 0 |
| North America | 2 | 50 | 50 | 100 | 100 | 50 |
| World | 112 | 12 | 14 | 42 | 54 | 11 |

*Notes: Figures indicate the proportion of countries reporting the use of specific biotechnologies for any of the big five species.*
*Source: Country reports, 2025.*

Table 3E3 presents the use of the various technologies across all 28 species groups covered in the country questionnaires. A larger proportion of countries reported using these technologies for the “big five” species, with the exception of chicken, for which only transplantation of gonadal tissue showed slightly higher usage compared to other species. For the four other species for instance, a majority of countries reported the use of artificial insemination. Among the minor species, only horses and buffaloes were reported to have relatively widespread use of the technologies (with mithun also showing notable use of AI and ET). It is also noteworthy that 36 percent and 30 percent of countries reported the use of artificial insemination and molecular genetic and genomic information, respectively, for managed bees.

**Table 3E3. Use of reproductive and molecular technologies for all species**

| Category | Species | Number of countries reporting the species | Artificial insemination | Embryo transfer | Molecular genetic or genomic information | Multiple ovulation and embryo transfer | Semen sexing | In vitro fertilization | Cloning | Genetic engineering | Transplantation of gonadal tissue |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Big five species | Dairy cattle | 101 | 96 | 69 | 53 | 59 | 55 | 44 | 11 | 10 | 6 |
| | Beef cattle | 90 | 88 | 63 | 48 | 54 | 48 | 41 | 8 | 9 | 6 |
| | Multipurpose cattle | 89 | 88 | 51 | 52 | 43 | 33 | 33 | 6 | 4 | 3 |
| | Sheep | 108 | 59 | 31 | 45 | 21 | 4 | 15 | 7 | 6 | 1 |
| | Goats | 109 | 61 | 24 | 40 | 18 | 4 | 13 | 6 | 6 | 2 |
| | Pigs | 96 | 78 | 19 | 35 | 16 | 8 | 10 | 7 | 8 | 2 |
| | Chickens | 108 | 33 | 1 | 22 | 1 | 3 | 2 | 1 | 6 | 7 |
| Other mammals | Alpacas | 6 | 17 | 17 | 17 | 17 | 0 | 0 | 17 | 0 | 0 |
| | Asses | 41 | 24 | 10 | 22 | 5 | 0 | 5 | 2 | 0 | 0 |
| | Bactrian camels | 9 | 22 | 11 | 22 | 11 | 0 | 11 | 0 | 0 | 0 |
| | Buffaloes | 32 | 81 | 31 | 31 | 25 | 13 | 28 | 3 | 0 | 0 |
| | Deer | 11 | 18 | 9 | 27 | 9 | 0 | 18 | 0 | 0 | 0 |
| | Dromedaries | 27 | 15 | 7 | 19 | 4 | 0 | 4 | 0 | 0 | 0 |
| | Guinea pigs | 8 | 13 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Horses | 85 | 66 | 42 | 34 | 26 | 5 | 18 | 5 | 5 | 1 |
| | Llamas | 5 | 20 | 20 | 0 | 20 | 0 | 0 | 0 | 0 | 0 |
| | Mithun | 3 | 67 | 33 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Rabbits | 58 | 19 | 2 | 16 | 2 | 0 | 2 | 2 | 3 | 0 |
| | Yaks | 6 | 33 | 17 | 17 | 0 | 0 | 0 | 0 | 0 | 0 |
| Other poultries | Ducks | 59 | 8 | 0 | 14 | 0 | 2 | 0 | 0 | 0 | 0 |
| | Geese | 39 | 13 | 0 | 18 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Guinea fowls | 29 | 7 | 0 | 10 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Muscovy ducks | 18 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Ostriches | 19 | 5 | 0 | 11 | 0 | 5 | 5 | 5 | 5 | 5 |
| | Pigeons | 29 | 3 | 0 | 7 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Quails | 27 | 7 | 0 | 7 | 0 | 0 | 0 | 0 | 4 | 0 |
| | Turkeys | 37 | 11 | 0 | 16 | 0 | 0 | 0 | 0 | 3 | 3 |
| Bees | Managed bee | 74 | 36 | 1 | 30 | 0 | 3 | 1 | 0 | 0 | 0 |

*Notes: Figures indicate the proportion of countries reporting the use of specific biotechnologies at least at a low level*
*Source: Country reports, 2025.*

Table 3E4 provides a species-specific breakdown of the reported scores for the availability of different technologies across the five major livestock species, while Figure 3E1 illustrates the frequency distribution of these availability scores by region and species. Only in the case of dairy cattle and artificial insemination (AI) was the average availability reported between medium and high (i.e. between 2 and 3), meaning "available to livestock keepers in some locations or production systems" to "widely available to livestock keepers." For all other species, the average availability of AI was reported between low ("at experimental level only") and medium for meat and multipurpose cattle and pigs, and lower still for the remaining species. This aligns with the finding that dairy cattle was the only category in which a majority of countries (59 percent) indicated that AI was widely available. By contrast, only about 25 percent of countries reported wide availability of AI for meat and multipurpose cattle and pigs. To address persistent constraints in access to artificial insemination services, innovative delivery models have emerged, including drone-enabled semen delivery in Rwanda (Box 2E4).

**Box 2E4. Drone-enabled semen delivery in Rwanda: a model for last-mile reproductive services.**

In Rwanda, drone-enabled delivery of pig semen has emerged as a practical innovation for strengthening access to AI services in rural areas. Implemented through collaboration among the Rwanda Agriculture and Animal Resources Development Board (RAB), Zipline, and the USAID Orora Wihaze project, the system addresses a key operational constraint in reproductive biotechnology: the timely transport of semen to points of use while maintaining quality and minimizing delays. This challenge is particularly acute in smallholder systems, where distance, limited transport options and uneven service coverage often restrict access to AI, thereby constraining the uptake of improved breeding services (Marshall & Hirwa, 2024; Manikuzwe *et al.*, 2026).

The relevance of this model to AnGR management lies in its capacity to extend the practical use of reproductive technologies without requiring livestock keepers to be located close to semen production or storage facilities. In the Rwandan pig sector, drone delivery has been described as unique in East Africa, with semen transported from two distribution centres to veterinarians and service providers across different regions of the country. Recent peer-reviewed analysis indicates that drone-enabled semen delivery has improved service responsiveness in rural settings and, when combined with training and awareness-raising activities, has helped reduce cold-chain failures and losses due to expired semen, thereby improving AI outcomes in the intervention areas (Manikuzwe *et al.*, 2026). The project is estimated to have resulted in 4 489 inseminations and 28 553 piglets, generating a total economic impact of approximately USD 2.3 million.

Beyond the Rwandan context, this example highlights that the effectiveness of reproductive biotechnologies depends not only on biological techniques, but also on the systems that enable the movement of germplasm, information and services. In this sense, drone-enabled delivery provides an illustrative case of how digital and transport innovations can support the wider use of reproductive technologies in livestock systems where conventional infrastructure remains weak. At the same time, the contribution of such approaches to AnGR management will depend on the extent to which they are integrated into coherent breeding strategies and made accessible across diverse production systems.

For the other technologies, average availability was reported between low and medium for ET in both dairy and beef cattle, and for semen sexing, MOET, and the use of molecular genetic and genomic information in the case of dairy cattle. Regionally, Europe and North America were the only regions in which the average availability of AI exceeded 40 percent across the five major species. In North America, the use of molecular genetic and genomic information was the only other technology reported as widely available for a majority of species (77 percent). North America also reported medium to high levels of availability for ET and MOET in most species x country combination, while Europe reported medium to high availability specifically for molecular genetic and genomic information in a majority of cases.

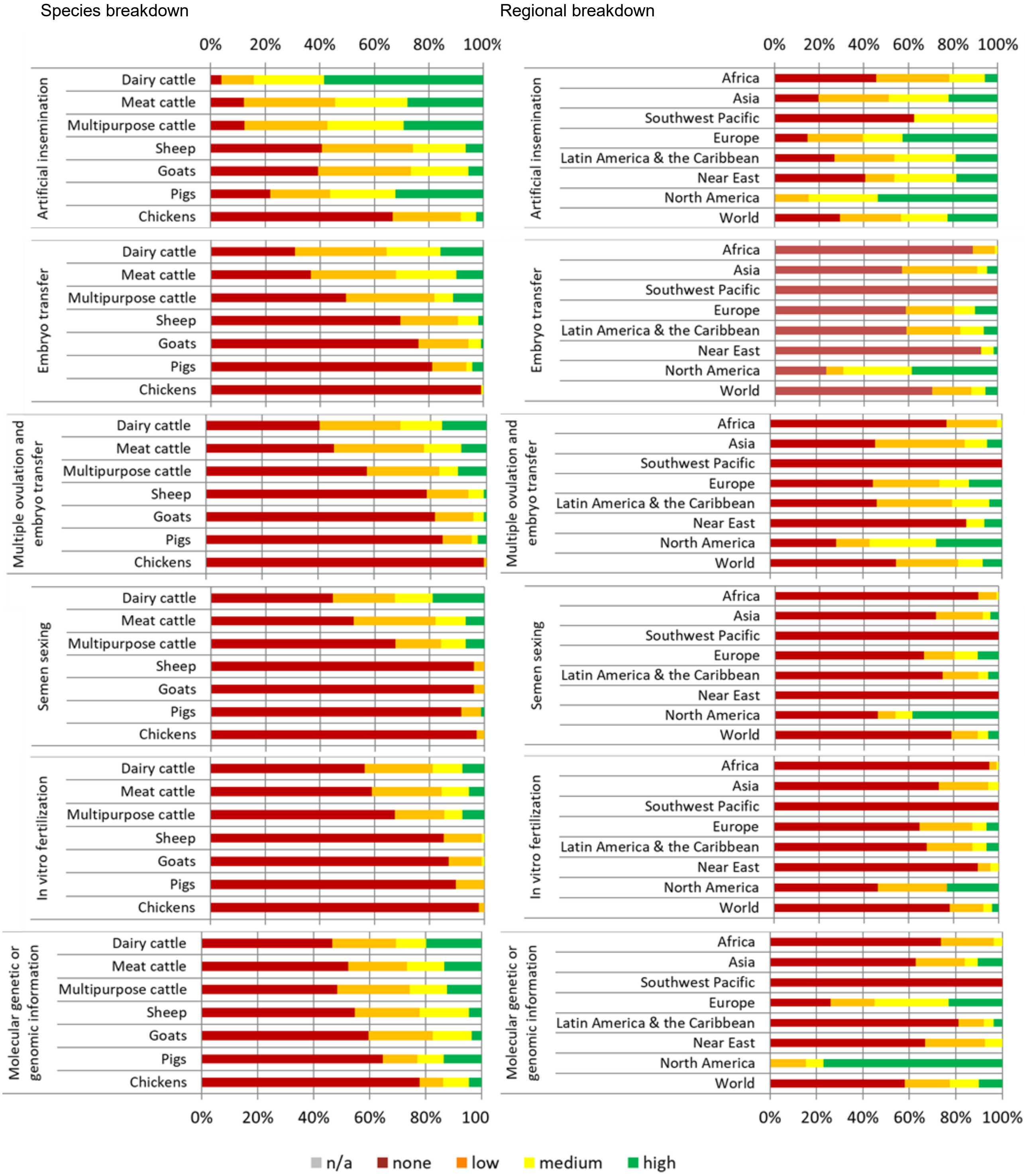
Outside these regions, most countries reported that the majority of technologies were not available beyond the experimental level. In particular, cloning, genetic engineering, and transplantation of gonadal tissue all received average scores barely above 0.1, indicating that their use remains almost exclusively experimental. For this reason, results for these three technologies are not displayed in Figures 3E1 and 3E2.

**Table 3E4. Level of availability of reproductive and molecular technologies for use in livestock production – big five species**

| Technology | Dairy cattle | | Beef cattle | | Multi-purpose cattle | | Chickens | | Goats | | Pigs | | Sheep | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | n = 101 | | n = 90 | | n = 89 | | n = 108 | | n = 109 | | n = 96 | | n = 108 | |
| | t | Score | t | Score | t | Score | t | Score | t | Score | t | Score | t | Score |
| Artificial insemination | 97 | 2.4 | 79 | 1.7 | 78 | 1.7 | 36 | 0.4 | 66 | 0.9 | 75 | 1.7 | 64 | 0.9 |
| Cloning | 11 | 0.1 | 7 | 0.1 | 5 | 0.1 | 1 | 0.0 | 6 | 0.1 | 7 | 0.1 | 8 | 0.1 |
| Embryo transfer | 70 | 1.2 | 57 | 1.1 | 45 | 0.8 | 1 | 0.0 | 26 | 0.3 | 18 | 0.3 | 33 | 0.4 |
| Genetic engineering | 10 | 0.1 | 8 | 0.1 | 4 | 0.0 | 7 | 0.1 | 7 | 0.1 | 8 | 0.1 | 7 | 0.1 |
| In vitro fertilization | 44 | 0.7 | 37 | 0.6 | 29 | 0.6 | 2 | 0.0 | 14 | 0.1 | 10 | 0.1 | 16 | 0.2 |
| Molecular genetic or genomic information | 54 | 1.0 | 43 | 0.9 | 46 | 0.9 | 24 | 0.4 | 44 | 0.6 | 34 | 0.7 | 49 | 0.7 |
| Multiple ovulation and embryo transfer | 60 | 1.1 | 49 | 0.9 | 38 | 0.7 | 1 | 0.0 | 20 | 0.2 | 15 | 0.2 | 23 | 0.3 |
| Semen sexing | 56 | 1.1 | 43 | 0.7 | 29 | 0.6 | 3 | 0.0 | 4 | 0.0 | 8 | 0.1 | 4 | 0.0 |
| Transplantation of gonadal tissue | 6 | 0.1 | 5 | 0.1 | 3 | 0.0 | 8 | 0.1 | 2 | 0.0 | 2 | 0.0 | 1 | 0.0 |

*Note: Availability was scored on the following scale: none (0); low – at experimental level only (1); medium – available to livestock keepers in some locations or production systems (2); or high – widely available to livestock keepers (3). Responding to this question was optional. The scores shown are averages for the countries that provided answers to this question.*
*Source: Country reports, 2014.*

**Figure 3E1. Level of availability of reproductive technologies (big five species)**




*Notes: The bar charts show the proportion of responses falling into the none, low, medium and high categories of level of availability (see legend). The charts on the left show the overall proportion of countries that provided the respective response for the respective species. The charts on the right show the proportion of answers (country × species combinations) from the respective region falling into the respective category.*
*Source: Country reports, 2025.*

Textual comments from countries corroborated the increased use of AI in cattle, with India noting that AI is now also used in the field for buffalo, while most other reproductive technologies remain at an experimental stage. Colombia emphasized that the widespread adoption of AI is strongly dependent on the availability of skilled personnel and efficient commercial distribution networks. Several countries also highlighted constraints: Guinea, for example, reported insufficient technical expertise, an inadequate number of trained technicians, difficulties obtaining liquid nitrogen, and problems related to inputs and storage infrastructure. Peru noted that although only a minority of small- and medium-scale producers currently apply reproductive biotechnologies like AI, the proportion has doubled over the last decade. The country reported active experimental work on South American camelids and guinea pigs, while underlining challenges linked to species-specific reproductive physiology.

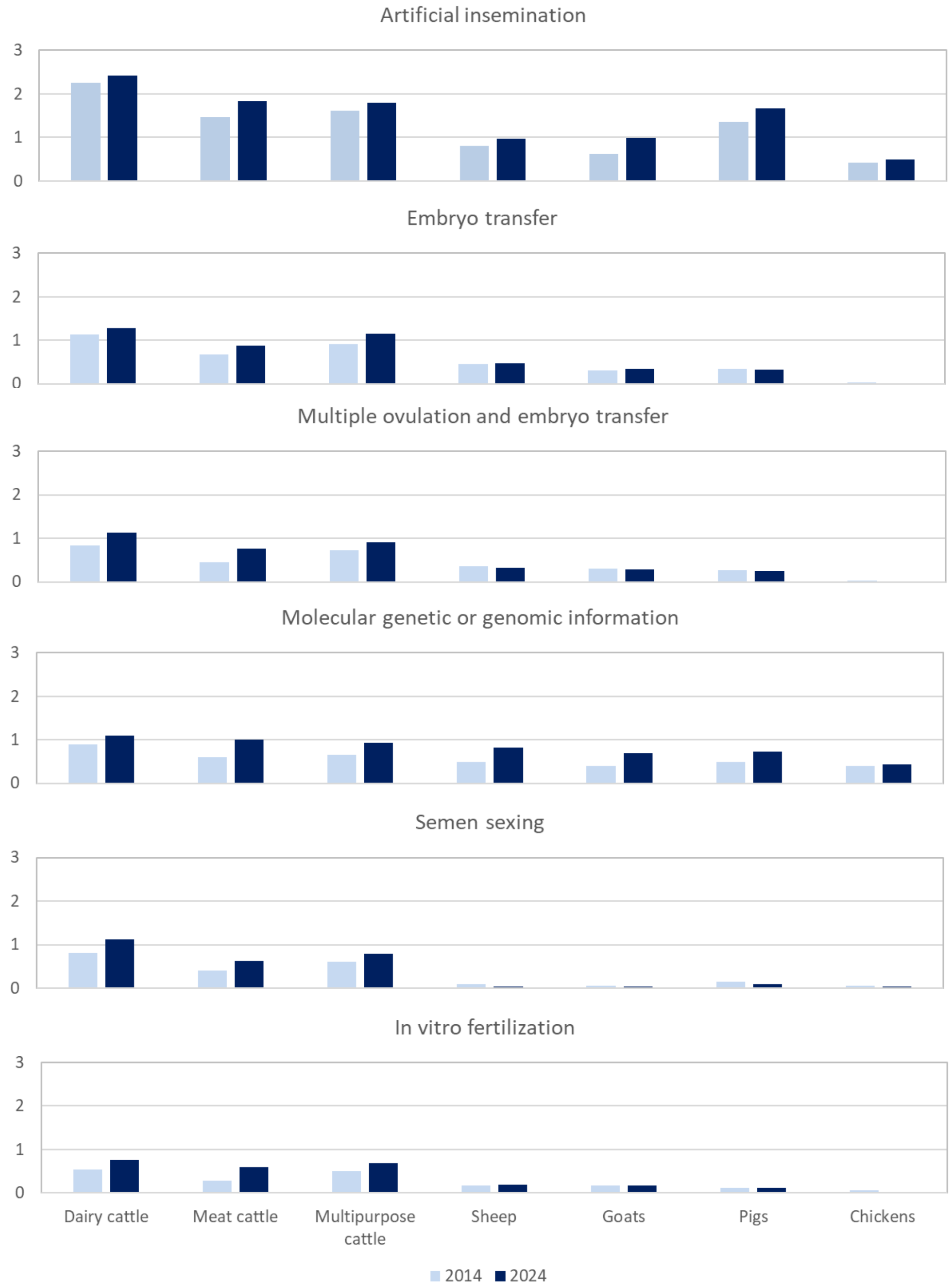
Regarding other technologies, Brazil reported widespread use of in vitro fertilization and ET, mainly in cattle but also, to a lesser extent, in horses and sheep. Countries such as Denmark and Namibia highlighted the wide use of genomic selection in commercial breeds, while—beyond breeding applications—many countries reported genotyping or whole-genome sequencing of local populations (for example, the Philippines for Swamp buffalo). By contrast, Saudi Arabia indicated that it is still at an early stage of applying reproductive and molecular technologies, supported by the recent establishment of a center of excellence in genomic technologies for animal breeding.

On cloning, the Republic of Korea indicated that national institutions and companies are producing transgenic cloned pigs for organ transplantation, whereas India reported being the first country in the world to clone a buffalo using a hand-guided technique. With regard to genetic engineering, countries reported results mostly at experimental stage, such as Peru's use of CRISPR-Cas9 gene knockout of myostatin in guinea pigs to enhance muscularity, or Poland's cloning of genetically modified pigs with humanized immune systems, as well as work on transgenic goats and chimeric cloning in rabbits.

Beyond these examples, countries identified several factors limiting the adoption of biotechnologies, including shortages of skilled personnel, insufficient infrastructure, high costs, limited funding, and public or user acceptance issues. Côte d'Ivoire, for instance, explained that because the main national facility for producing semen and training technicians no longer exists, the country has become dependent on external suppliers. South Africa noted that adoption in low-input systems remains difficult due to cost, limited awareness, inadequate training, and resource constraints. Portugal pointed to rising costs, exacerbated by limited technical and logistical capacity, along with the aging demographic of producers, as key barriers to expanding the use of these technologies.

Figure 3D2 compares the average availability levels of the reproductive technologies described above with the corresponding results from the second SoW-AnGR reporting cycle, considering only the 93 countries that participated in both processes (big five species). Relative progress was reported for the use of molecular genetic and genomic information (+0.3 on average) and for artificial insemination (+0.2 on average). For ET, MOET, semen sexing and in vitro fertilization, progress was limited (+0.1). No progress was reported for cloning, genetic engineering, or transplantation of gonadal tissue (data not shown). Progress were more marked for cattle (+0.2), more limited for other mammals (+0.1) and no progress was observed for chicken.

**Figure 3E2. Progress in the level of availability of reproductive technologies between 2014 and 2025 (big five species)**




*Notes: Level of availability was scored none (0), low (1), medium (2) or high (3) by the 93 countries having answered to both 2014 and 2025 reports. The scores shown represent averages calculated across the countries that reported data for each species, with missing responses for this question in the 2014 report treated as a score of 0.*
*Source: Country reports, 2014, 2025.*

To assess differences between production systems (see the *Second Report on the State of the World's Animal Genetic Resources*, (FAO, 2015) for detailed descriptions) in the use of artificial insemination (AI), as well as in the sources of semen used, countries were asked to indicate, using a scoring system, the relative contributions of the following to the total number of matings/inseminations in each production system present in the country: natural mating, AI using semen from locally adapted breeds, AI using nationally produced semen from exotic breeds, and AI using imported semen. The summarized results are shown in Table 3E5. Across the various production systems considered, industrial systems were reported to rely less on natural mating for all four major mammalian species and to make greater use of imported semen from exotic breeds, particularly in the case of dairy cattle and pigs. In most species and production systems, the three forms of AI use (locally adapted breeds, nationally produced semen from exotic breeds, and imported semen) were reported at roughly similar levels. The main exception was dairy cattle, for which countries indicated a greater reliance on imported semen from exotic breeds. In contrast, pastoral production systems were reported to make the least use of imported semen from exotic breeds; however, they were not consistently reported to rely more on natural mating than other non-industrial systems. Overall, cattle and pigs (particularly within industrial systems) showed a higher reliance on AI in general, whereas goats and sheep were reported to depend more heavily on natural mating, regardless of production system.

**Table 3E5. Level of use of artificial insemination and sources of semen (four main mammals species considered)**

| Species | Production system | Imported semen from exotic breeds | Nationally produced semen from exotic breeds | Semen from locally adapted breeds | Natural mating |
|---|---|---|---|---|---|
| | | Score (0–3) | | | |
| Dairy cattle | Pastoralist | 0.8 | 0.5 | 0.7 | 1.5 |
| | Ranching | 1.4 | 1.1 | 1.0 | 1.5 |
| | Mixed farming | 1.5 | 1.1 | 1.0 | 1.5 |
| | Small-scale (peri)urban | 1.3 | 0.9 | 0.7 | 1.4 |
| | Industrial | 1.8 | 1.1 | 1.0 | 1.0 |
| Beef cattle | Pastoralist | 0.7 | 0.5 | 0.5 | 1.9 |
| | Ranching | 1.2 | 0.9 | 0.8 | 2.3 |
| | Mixed farming | 1.0 | 0.8 | 0.8 | 2.2 |
| | Small-scale (peri)urban | 0.7 | 0.5 | 0.5 | 1.6 |
| | Industrial | 1.0 | 0.7 | 0.6 | 1.4 |
| Multipurpose cattle | Pastoralist | 0.8 | 0.7 | 0.6 | 2.2 |
| | Ranching | 1.2 | 1.0 | 0.9 | 2.5 |
| | Mixed farming | 1.1 | 0.9 | 1.0 | 2.2 |
| | Small-scale (peri)urban | 0.9 | 0.7 | 0.6 | 1.8 |
| | Industrial | 1.1 | 0.8 | 0.7 | 1.1 |
| Goat | Pastoralist | 0.2 | 0.2 | 0.2 | 2.2 |
| | Ranching | 0.4 | 0.3 | 0.3 | 2.6 |
| | Mixed farming | 0.4 | 0.3 | 0.4 | 2.5 |
| | Small-scale (peri)urban | 0.3 | 0.2 | 0.2 | 2.3 |
| | Industrial | 0.5 | 0.3 | 0.4 | 1.8 |
| Pig | Pastoralist | 0.3 | 0.2 | 0.1 | 1.6 |
| | Ranching | 0.5 | 0.4 | 0.3 | 2.0 |
| | Mixed farming | 0.6 | 0.8 | 0.6 | 2.0 |
| | Small-scale (peri)urban | 0.5 | 0.6 | 0.3 | 1.9 |
| | Industrial | 1.2 | 1.4 | 0.9 | 1.4 |
| Sheep | Pastoralist | 0.2 | 0.2 | 0.3 | 2.2 |
| | Ranching | 0.4 | 0.3 | 0.4 | 2.5 |
| | Mixed farming | 0.3 | 0.3 | 0.3 | 2.4 |
| | Small-scale (peri)urban | 0.2 | 0.2 | 0.2 | 2.1 |
| | Industrial | 0.4 | 0.5 | 0.4 | 1.7 |

*Note: The figures represent average scores for the extent to which artificial insemination and natural mating is used in the respective species in the respective production system. The following scoring system was used: none (0); low – approximately <33% of matings – (1); medium – approximately 33–66% of matings – (2); high – approximately >67% of matings – (3); or "production system not present in this country". Countries where a given species × production system combinations does not exist were excluded from the calculation of the respective average score.*
*Source: Country reports, 2025.*

# 4. Stakeholders involved in service provision and research on reproductive and molecular biotechnologies

The country-report questionnaire asked countries to indicate which stakeholders are involved in providing AI and ET services to livestock keepers, selecting from a list that included the public sector, breeders' associations or cooperatives, national non-governmental organizations (NGOs), donors and development agencies, national commercial companies, and external commercial companies. The results are summarized in Table 3E6. Globally, the public sector, breeders' associations or cooperatives, and national commercial companies emerged as the main providers of these services, although regional differences are notable. In Asia, almost all countries reported involvement of the public sector (100 percent for AI). In Europe, Latin America and the Caribbean, a large proportion of countries highlighted the involvement of breeders' associations or cooperatives. Countries in these two regions, as well as in Asia, also frequently reported the involvement of national commercial companies. In contrast, in Africa, a majority of countries indicated that national NGOs play an important role in delivering AI services, significantly above the global average of 34 percent.

**Table 3E6. Stakeholder involvement in the provision of artificial insemination and embryo transfer services**

| Regions | Technology | Number of countries | Breeders' associations or cooperatives | Donors and development agencies | External commercial companies | National commercial companies | National non-governmental organizations | Public sector |
|---|---|---|---|---|---|---|---|---|
| | | | % | | | | | |
| Africa | AI | 35 | 60 | 51 | 30 | 56 | 55 | 80 |
| | ET | 33 | 9 | 9 | 12 | 12 | 3 | 30 |
| Asia | AI | 13 | 54 | 46 | 38 | 92 | 38 | 100 |
| | ET | 13 | 38 | 38 | 31 | 62 | 38 | 77 |
| Southwest Pacific | AI | 2 | 50 | 0 | 0 | 0 | 0 | 50 |
| | ET | 2 | 0 | 0 | 0 | 0 | 0 | 0 |
| Europe | AI | 30 | 86 | 4 | 59 | 87 | 19 | 64 |
| | ET | 28 | 59 | 4 | 44 | 78 | 19 | 57 |
| Latin America & the Caribbean | AI | 17 | 82 | 35 | 59 | 88 | 29 | 82 |
| | ET | 16 | 75 | 19 | 56 | 81 | 25 | 50 |
| Near East | AI | 11 | 45 | 27 | 18 | 45 | 36 | 73 |
| | ET | 11 | 0 | 0 | 0 | 9 | 0 | 36 |
| North America | AI | 2 | 50 | 0 | 100 | 50 | 0 | 50 |
| | ET | 2 | 50 | 0 | 100 | 50 | 0 | 50 |
| World | AI | 110 | 66 | 31 | 41 | 71 | 34 | 75 |
| | ET | 105 | 35 | 11 | 30 | 46 | 14 | 47 |

*Notes: AI = artificial insemination; ET = embryo transfer. "Number of countries" = the number of countries that report the availability of the respective technology at least at a low level for at least one species.*
*Source: Country reports, 2025.*

In their reports, countries detail a range of modalities regarding the provision of reproductive and molecular biotechnologies, from Algeria, indicating that a National AI Centre (CNIAAG) under the Ministry provides almost all semen from improved or imported cattle, to United States of America, underlining an implementation primarily by private companies in competitive markets. In many case, multiparner governance arrangements are reported, with Austria combining public institutions, breeding associations, NGOs, and commercial companies for AI, ET/MOET and genomic services, and Italy assigning breed societies to manage selection schemes, private companies to produce and market germplasm, and the government to regulate germplasm trade, all together illustrating coordinated, multi-actor systems for implementing AnGR biotechnologies. On the other hand, challenges are also reported in the governance, infrastructure, and especially human capacities, Botswana reporting for instance, that due to the limited numbers of skilled personnel on ET in the country, some farmers outsource such service from external companies especially from South Africa. In that extent, a wide range of stakeholders are involved, often jointly, in building capacities for biotechnology implementation, Malawi and Uganda reporting public institutions, farmer organizations, NGOs and commercial companies collaborate extensively in training and technology transfer. In some case, research and universities are reported to involved in the commercialization of semen, and in 2023, the

Ministry of Agricultural Development and Irrigation of Peru granted certification to the Toribio Rodríguez de Mendoza National University to market genetic material (semen and embryos) nationwide. France also underlined re-configuration of the breeding programme governance around genomic data, with for instance increasing use of sexed semen distributed by international commercial companies.

Countries were also asked to indicate whether they are conducting research on the biotechnologies discussed in this section. The results are summarized in Tables 3E7 and 3E8. Regarding reproductive biotechnologies, AI was reported as a topic of national-level research by a majority of countries in all regions except the Southwest Pacific. Similarly, more than half of the countries in North America, Asia, Europe, and Latin America and the Caribbean reported conducting national research on MOET and in vitro fertilization. Globally, one third of countries—and a majority only in North America and Asia—reported national-level research on semen sexing. Fewer than 20 percent of countries indicated research on cloning. In general, international collaboration was reported less frequently than national-level research. The main exception was the Near East, where the proportion of countries reporting international collaboration was similar to, or in the case of semen sexing even greater than, the proportion reporting national research.

**Table 3E7. Proportion of countries reporting research on reproductive biotechnologies**

| Regions | Number of countries | Artificial insemination | | Embryo transfer or MOET | | Semen sexing | | In vitro fertilization | | Cloning | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | National | International | National | International | National | International | National | International | National | International |
| | | % | | | | | | | | | |
| Africa | 35 | 69 | 54 | 34 | 34 | 6 | 14 | 17 | 17 | 3 | 9 |
| Asia | 14 | 100 | 43 | 86 | 43 | 64 | 36 | 64 | 29 | 43 | 21 |
| Europe | 31 | 87 | 55 | 81 | 45 | 48 | 45 | 71 | 48 | 26 | 26 |
| Southwest Pacific | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Latin America & the Caribbean | 17 | 71 | 41 | 65 | 35 | 47 | 18 | 71 | 24 | 18 | 12 |
| Near East | 11 | 64 | 64 | 27 | 27 | 18 | 36 | 27 | 27 | 9 | 9 |
| North America | 2 | 100 | 50 | 100 | 50 | 100 | 50 | 100 | 50 | 50 | 0 |
| World | 112 | 77 | 51 | 58 | 38 | 34 | 29 | 48 | 29 | 18 | 15 |

*Note: "National" refers to public or private research at national level and "international" refers to research undertaken as part of international collaboration.*
*Source: Country reports, 2025*

When considering research on molecular biotechnologies, fewer than 20 percent of countries worldwide reported activities, either at the national or international level, related to genetic engineering. Approximately half of all countries indicated that they are conducting research on the use of molecular genetic or genomic information, with a larger proportion focusing on the estimation of genetic diversity than on breeding-value prediction, and an even smaller proportion on adaptedness. The proportion of countries reporting such research was particularly high in North America and Europe. However, even in Africa, Latin America and the Caribbean, and the Near East, almost half of the countries reported conducting research on the estimation of genetic diversity. As with reproductive biotechnologies, a slightly larger proportion of countries reported research conducted at the national level compared with those reporting international collaboration.

**Table 3E8. Proportion of countries reporting research on molecular biotechnologies**

| Regions | Number of countries | Genetic engineering | | Use of molecular genetic or genomic information | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | for estimation of genetic diversity | | for prediction of breeding values | | for research on adaptedness | |
| | | National | International | National | International | National | International | National | International |
| | | % | | | | | | | |
| Africa | 35 | 6 | 14 | 49 | 46 | 29 | 37 | 29 | 31 |
| Asia | 14 | 29 | 21 | 86 | 29 | 57 | 21 | 57 | 21 |
| Southwest pacific | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Europe | 31 | 23 | 19 | 90 | 84 | 87 | 77 | 77 | 65 |
| Latin America & the Caribbean | 17 | 24 | 24 | 47 | 35 | 59 | 29 | 35 | 18 |
| Near East | 11 | 9 | 0 | 45 | 36 | 9 | 9 | 18 | 18 |
| North America | 2 | 100 | 50 | 100 | 100 | 100 | 50 | 100 | 50 |
| World | 112 | 18 | 17 | 64 | 52 | 52 | 42 | 46 | 36 |

*Note: "National" refers to public or private research at national level; "international" refers to research undertaken as part of international collaboration.*
*Source: Country reports, 2025*



Countries reported a wide range of research activities undertaken at the national level. For example, Argentina described extensive public–private research on topics ranging from hormonal protocols for AI and cryopreservation of gametes and embryos, to the development of gene-editing platforms, as well as the selection of disease-resistant bee lines using controlled crossbreeding and instrumental insemination. Ethiopia highlighted molecular genetic research conducted mainly within academic institutions, particularly postgraduate studies focused on the characterization and adaptive traits of indigenous AnGR. In several cases, countries also identified important research gaps. Tunisia noted a national shortfall in molecular-level research despite progress in characterization and evaluation methods, while Cambodia reported the absence of biotechnology-related research due to a lack of supporting projects, funding, facilities, and qualified personnel. Examples of international collaboration were equally diverse. Pakistan reported undertaking ET research in partnership with a Chinese company, alongside collaborative work with U.S. agencies on the application of genomic tools for breeding evaluation in goats. Yemen, in cooperation with the Arab Center for the Studies of Arid Zones and Dry Lands (ACSAD), implemented artificial insemination using frozen Awassi sheep semen to test crosses with local breeds under research-station conditions. The Republic of Korea highlighted an international dairy-cattle genetic evaluation programme jointly developed with the German organization Vereinigte Informationssysteme Tierhaltung w.V. (VIT).

# 5. Report on capacities in information and communication technologies

Although no question in the country questionnaire addressed the use of information and communication technologies (ICTs) directly, the topic was raised repeatedly in the comments. In Europe in particular, countries such as Norway and Ireland highlighted the major impact of precision agriculture and digitalization on livestock management systems. Senegal reported that, while reproductive biotechnologies have been theoretically available for more than 30 years, their uptake remains limited due to financial, infrastructural and capacity constraints, in contrast to digital tools that support electronic payments or provide access to market price information. Several other countries, including Slovenia, Thailand and Uganda, also emphasized the role of digital platforms and tools in streamlining data collection, shaping consumer preferences and raising awareness of the importance of animal genetic resources (crossference to Box 2B1).

# 6. Conclusions and priorities

Over the past decade, reproductive and molecular biotechnologies have continued to expand their technical maturity and scope, with artificial insemination remaining the most widely applied and operationally established tool across livestock species. Progress has been most evident in the refinement and integration of established reproductive technologies, improvements in quality control and efficiency, and the progressive incorporation of genomic and other molecular approaches into characterization and breeding programmes. Nevertheless, adoption remains more than ever highly uneven across regions, species and production systems, reflecting persistent constraints related to infrastructure, funding, skilled human resources, governance arrangements and socioethical considerations. The involvement of stakeholders in the provision of related services varies markedly across regions, with differing roles played by public institutions, breeders' organizations, commercial companies, non-governmental organizations and international actors. Advanced technologies such as cloning, genetic engineering and gonadal tissue transplantation continue to be largely confined to experimental settings, while the practical use of molecular and omicsbased tools beyond major commercial species remains limited.

At the same time, rapid advances in information and communication technologies have become an increasingly important enabling factor for animal genetic resources management, supporting data generation, integration and decision support across breeding, conservation and production contexts. Precision livestock farming, sensor technologies, automation and data-driven management tools are now well established in intensive systems and are beginning to offer applications relevant to a wider range of production environments. However, their effective contribution to AnGR management depends on addressing challenges related to data quality, interoperability, governance and equitable access, particularly in lowinput and extensive systems. Looking ahead, strengthening national capacities will require coordinated investments in infrastructure, skills development and institutional frameworks, as well as the strategic integration of reproductive, molecular and digital technologies within coherent and sustainable AnGR management strategies.

## References


**Akhigbe, B.I., Munir, K., Akinade, O., Akanbi, L. & Oyedele, L.O.** 2021. IoT technologies for livestock management: a review of present status, opportunities and future trends. *Big Data and Cognitive Computing*, 5(1): 10. https://doi.org/10.3390/bdcc5010010

**Althouse, G.C.** 2024. Contaminant toxicity of concern for boars and semen used in assisted reproduction programs. *Animal Reproduction Science*, 269: 107519, https://doi.org/10.1016/j.anireprosci.2024.107519.

**Azevedo, H.C., Blackburn, H.D., Lozada-Soto, E.A., Spiller, S.F., & Purdy, P.H.** 2024. Enhancing evaluation of bull fertility through multivariate analysis of sperm. *Journal of Dairy Science*, 107: 11774-11784, doi: 10.3168/jds.2024-25163. Epub 2024 Sep 27. PMID: 39343204.

**Bodu, M., Hitit, M., Greenwood, O.C., Murray, R.D., & Memili, E.** 2025. Extender development for optimal cryopreservation of buck sperm to increase reproductive efficiency of goats. *Frontiers in Veterinary Science,* 12: 1554771, doi: 10.3389/fvets.2025.1554771.

**Brito, L.F.C.** 2024. Quality assurance applied to semen analysis. *Animal Reproduction Science*, 270: 107615, https://doi.org/10.1016/j.anireprosci.2024.107615.

**Brito, L. F., Heringstad, B., Klaas, I. C., Schodl, K., Cabrera, V. E., Stygar, A., ... & Egger-Danner, C.** 2025. Invited review: Using data from sensors and other precision farming technologies to enhance the sustainability of dairy cattle breeding programs. *Journal of Dairy Science*, *108*(10), 10447-10474. https://doi.org/10.3168/jds.2025-26554

**Chakraborty, D., Sharma, N., Kour, S., Sodhi, S. S., Gupta, M. K., Lee, S. J., & Son, Y. O.** 2022. Applications of omics technology for livestock selection and improvement. *Frontiers in genetics*, *13*, 774113.

**Clasen, J. B., Fikse, W. F., Su, G., & Karaman, E.** 2023. Multibreed genomic prediction using summary statistics and a breed-origin-of-alleles approach. *Heredity*, *131*(1), 33-42.

**Daum, T., Ravichandran, T., Kariuki, J., Chagunda, M. & Birner, R.** 2022. Connected cows and cyber chickens? Stocktaking and case studies of digital livestock tools in Kenya and India. Agricultural Systems, 196: 103353. https://doi.org/10.1016/j.agsy.2021.103353

**Garcia-Canovas, M., Parrilla, I., Cuello, C., Gil, M.A., & Martinez, E.A.** 2024. Swine in vitro embryo production: Potential, challenges, and advances. *Animal Reproduction Science*, 270: 107600, https://doi.org/10.1016/j.anireprosci.2024.107600.

**FAO.** 2015. *The second report on the state of the world's animal genetic resources for food and agriculture*, edited by B.D. Scherf & D. Pilling. Rome, FAO. (available at: https://openknowledge.fao.org/server/api/core/bitstreams/464ecee6-d55c-407d-93bb-e9890ee88058/content).

**FAO.** 2017. *Information and communication technology (ICT) in agriculture: a report to the G20 Agricultural Deputies.* Rome.

**FAO.** 2026. *Information and Communication Technologies (ICT).* Electronic Platform on Agricultural and Rural Innovation (e-AIMS). Food and Agriculture Organization of the United Nations, Rome. Available at: https://aims.fao.org/information-and-communication-technologies-ict

**Georges, M., Charlier, C., & Hayes, B.** 2019. Harnessing genomic information for livestock improvement. *Nature Reviews Genetics*, *20*(3), 135-156.

**Gonçalves, J.D., Dias, J.H., Machado-Neves, M., Vergani, G.B., Ahmadi, B., Batista, R.I.T.P, Souza-Fabjan, J.H.G., Oliveira, M.E.F., Bartlewski, P.M., & Ferreira da Fonseca, J.** 2024. Transcervical uterine flushing and embryo transfer in sheep: Morphophysiological basis for approaches currently used, major challenges, potential improvements, and new directions (alas, including some old ideas). *Reproductive Biology*, 24: 100920, https://doi.org/10.1016/j.repbio.2024.100920.

**Guo, C., He, Z., Niu, M. & Liu, K.** 2025. Navigating AI deployment in precision livestock farming: current trends and future prospects. *Animal Frontiers*. https://doi.org/10.1093/af/vfaf050

**Hassanine, N. N., Saleh, A. A., Essa, M. O. A., Adam, S. Y., Mohai Ud Din, R., Rehman, S. U., *et al.*** 2025. Candidate Genes, Markers, Signatures of Selection, and Quantitative Trait Loci (QTLs) and Their Association with Economic Traits in Livestock: Genomic Insights and Selection. *International Journal of Molecular Sciences*, *26*(16), 7688.

**Hansen, P.J.** 2023. Review: Some challenges and unrealized opportunities toward widespread use of the in vitro-produced embryo in cattle production. *animal*, 17: Supplement 1, 100745, https://doi.org/10.1016/j.animal.2023.100745.

**Hu, T., Taylor, L., Sherman, A., Tiambo, C.K., Kemp, S.J., Whitelaw, B., Hawken, R.J., Djikeng, A., & McGrew, M.J.** 2022. A low-tech, cost-effective and efficient method for safeguarding genetic diversity by direct cryopreservation of poultry embryonic reproductive cells. eLife, 11:e74036, https://doi.org/10.7554/eLife.74036.

**ICAR.** 2026. *Genomic Era Begins: NDRI Initiates Selection Strategy for Sahiwal Cow Improvement*. Indian Council of Agricultural Research.

**Jinya, L.** 2024. Genomic Selection in Livestock Breeding: Advances and Applications. *Animal Molecular Breeding*, *14*.

**Khan, K. D., Alex, R., Yadav, A., Sahana, V. N., Upadhyay, A., Mani, R. V., ... *et al.*** 2025. Optimizing the genomic evaluation model in crossbred cattle for smallholder production systems in India. *Agriculture*, *15*(9), 945.

**Kumar, S., Magotra, A., Kumar, M., Dalal, D.S., & Kumari, S.** 2024. Semen sexing and its impact on fertility and genetic gain in cattle. *Zygote,* 32:109-118, doi:10.1017/S0967199424000066.

**Llavanera, M.** 2024. Evaluation of sperm quality and male fertility: The use of molecular markers in boar sperm and seminal plasma. *Animal Reproduction Science*, 269: 107545, https://doi.org/10.1016/j.anireprosci.2024.107545.

**Lucy, M.C., & Pohler, K.G.** 2025. North American perspectives for cattle production and reproduction for the next 20 years. *Theriogenology*, 232: 109-116, https://doi.org/10.1016/j.theriogenology.2024.11.006.

**Manikuzwe, J.M.P., Kremer, P. & Fadul, M.J.O.** 2026. From sky to sow: assessing the impact of drone-enabled semen delivery on pig fertility outcomes in rural Rwanda. Frontiers in Veterinary Science, 13: 1791617. https://doi.org/10.3389/fvets.2026.1791617

**Marshall, K., & Hirwa, C.** 2024. The pig genetic-resource value chain in Rwanda. Nairobi, Kenya, International Livestock Research Institute. Available at: https://cgspace.cgiar.org/bitstreams/3150a3ec-8ccc-4876-a655-b920021e8402/download

**Marzouk, E., & Alajaji, A.I.** 2025. Preventive Immunology for Livestock and Zoonotic Infectious Diseases in the One Health Era: From Mechanistic Insights to Innovative Interventions. *Veterinary Sciences*, *12*(10), 1014.

McKechnie, I., Raymond, K., Stacey, D.A. & Bernardo, T.M. 2025. Automating inconsistency discovery and historical investigation of external influences on livestock population data. Data Science Journal, 24. Available at: https://doi.org/10.5334/dsj-2025-026

**Mei, Q., Liu, H., Zhao, S., Xiang, T., & Christensen, O. F.** 2023. Genomic evaluation for two-way crossbred performance in cattle. *Genetics Selection Evolution*, *55*(1), 17.

**Mészáros, G., Curik, I., Windig, J. J., Leroy, G., Rosen, B., Utsunomiya, Y. T., ... & Sölkner, J.** 2026. Framework for assessing genetic variation in livestock using demographic, pedigree, and genomic measures. *Frontiers in Genetics*, *17*, 1792347.

**Morota, G., Lee, H. J., Lee, S. H., Park, H. B., & Onogi, A.** 2026. Artificial intelligence in animal breeding and genetics: Applications, opportunities, and challenges. *Animal Frontiers*, vfaf058.

**Nayee, N.** 2018. GS appeared promising in bull selection for HFCB for 1st lactation Milk Yield. In Proceedings of the World Congress on Genetics Applied to Livestock Production, Auckland, New Zealand, 11–16 February 2018; Volume 825.

**Neethirajan, S. & Kemp, B.** 2021. Digital livestock farming. *Sensing and BioSensing Research*, 32: 100408. https://doi.org/10.1016/j.sbsr.2021.10040

**Noor, S., Degroote, J., van Schaik, G., Pardon, B., Faverjon, C., Delavenne, C. & Hostens, M.** 2026. A systematic review on the role of livestock ontologies in animal health management and disease surveillance: A PRISMA 2020 and AI-assisted screening approach. *Smart Agricultural Technology*, 14: 101977. Available at: https://doi.org/10.1016/j.atech.2026.101977

**Pascottini, O.B., Crowe, A.D., Ramil, U.Y., Hostens, M., Opsomer, G., & Crowe, M.A.** 2025. Perspectives in cattle reproduction for the next 20 years – A European context. *Theriogenology*, 233: 8-23, https://doi.org/10.1016/j.theriogenology.2024.11.007.

**Pezo, F., Contreras, M.J., Zambrano, F., Uribe, P., Risopatron, J., Cesar de Andrade, A.F., Yeste, M., & Sánchez, R.** 2024. Thawing of cryopreserved sperm from domestic animals: Impact of temperature, time, and addition of molecules to thawing/insemination medium. *Animal Reproduction Science*, 268: 107572, https://doi.org/10.1016/j.anireprosci.2024.107572.

**Purdy, P.H., Redel, B., Chen, P., Rahe, A.J., Jivan, A., & Spiller, S.F.** 2025. Efficient collection of skin biopsies using the Tissue Sampling Unit® for subsequent cryopreservation and culture of fibroblasts. *Methods and Protocols*, in press.

**Rabaglino, M. B., Le Danvic, C., Schibler, L., Kupisiewicz, K., Perrier, J. P., O'Meara, C. M *et al.*** 2022. Identification of sperm proteins as biomarkers of field fertility in Holstein-Friesian bulls used for artificial insemination. *Journal of Dairy Science*, *105*(12), 10033-10046.

**Rodriguez-Martinez, H., Martinez-Serrano, C.A., Alvarez-Rodriguez, M., Martinez, E.A., & Roca, J.** 2024. Reproductive physiology of the boar: What defines the potential fertility of an ejaculate? *Animal Reproduction Science*, 269: 107476, https://doi.org/10.1016/j.anireprosci.2024.107476.

**Skrzyszowska, M. & Samiec, M.** 2021. Generating cloned goats by somatic cell nuclear transfer—Molecular determinants and application to transgenics and biomedicine. *International Journal of Molecular Science*, 22: 7490. https://doi.org/10.3390/.

**Souza-Fabjan, J.M.G., Oliveira, M.E.F., Guimarães, M.P.P., Brandão, F.Z., Bartlewski, P.M., & Fonseca, J.F.** 2023. Review: Non-surgical artificial insemination and embryo recovery as safe tools for genetic preservation in small ruminants. *animal*, 17: 100787, https://doi.org/10.1016/j.animal.2023.100787.

**STEM Prize.** 2021. iCow: new ways of doing old things. In: *10 Great African Innovations*. STEM Prize. https://stemprize.org/2021/11/18/__trashed-3/

**Tirpak, F., Hamilton, L.E., Schnabel, R.D., & Sutovsky, P.** 2024. Biomarker-based high-throughput sperm phenotyping: Andrology in the age of precision medicine and agriculture. *Animal Reproduction Science*, 271: 107636, https://doi.org/10.1016/j.anireprosci.2024.107636.

**Yang, Y., Wu, J., Liu, W., Zhao, Y., & Chen, H.** 2023. The function and regulation mechanism of non-coding RNAs in muscle development. *International journal of molecular sciences*, *24*(19), 14534.

**Yang, Y., Lin, M., Lin, Y., Zhang, C., & Wu, C.** 2025. A survey of blockchain applications for management in agriculture and livestock internet of things. *Future Internet*, *17*(1), 40.

**Waberski, D. & Luther, A-M.** 2024. Boar semen storage at 5 °C for the reduction of antibiotic use in pig insemination: Pathways from science into practice. *Animal Reproduction Science*, 269: 107486, https://doi.org/10.1016/j.anireprosci.2024.107486.

**Wadood, A. A., Bordbar, F., & Zhang, X.** 2025. Integrating omics approaches in livestock biotechnology: innovations in production and reproductive efficiency. *Frontiers in Animal Science*, *6*, 1551244.

**Wang, J., Zhang, L., Pan, C., Lan, X., Xing, B., & Li, M.** 2025. Application of Gene Editing Technology in Livestock: Progress, Challenges, and Future Perspectives. *Agriculture*, *15*(20), 2155.

**Zhao, Y., Yang, L., Su, G., Wei, Z., Liu, X., Song, L., *et al.*** 2022. Growth traits and sperm proteomics analyses of myostatin gene-edited Chinese yellow cattle. *Life*, *12*(5), 627.

**Zhang, Q., Zhang, J., Chang, G., Zhao, K., Yao, Y., Liu, L., *et al.* 2024**. Decoding molecular features of bovine oocyte fate during antral follicle growth via single-cell multi-omics analysis. *Biology of Reproduction*, *111*(4), 815-833.

**Zhou, C., Shen, D., Li, C., Cai, W., Liu, S., Yin, H., *et al.*** 2019. Comparative transcriptomic and proteomic analyses identify key genes associated with milk fat traits in Chinese Holstein cows. *Frontiers in genetics*, *10*, 672.