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Assisted reproductive technologies in livestock production and veterinary medicine: Biological foundations, innovations and field applications – A review

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Abstract

Assisted reproductive technologies (ARTs) have transformed livestock production by enabling precise control over gamete manipulation, fertilization and embryo development, accelerating genetic gain, and enhancing herd health. From artificial insemination (AI) to multiple ovulation and embryo transfer (MOET), in vitro fertilization (IVF), ovum pick-up (OPU), cryopreservation, genomic selection and gene editing, ARTs provide unprecedented capacity to optimize breeding outcomes and disseminate superior genetics. This review highlights the physiological foundations of reproduction and identifies the specific points where ART interventions can maximize fertility. Evidence demonstrates that species-specific reproductive traits, animal age, body condition and breed influence ART success, underscoring the need for tailored strategies. Integration with precision livestock farming and digital monitoring enhances oestrus detection, reproductive decision-making and biosecurity, while minimizing labour and improving welfare outcomes. Key takeaways include the identification of optimal intervention points for hormonal and embryo-based technologies, the critical role of genomics and molecular tools in accelerating genetic improvement, and the value of biosecurity and welfare safeguards for sustainable implementation. Adoption of ART must balance productivity gains with economic feasibility, ethical considerations and environmental sustainability. By synthesizing biological, technological and management dimensions, this review emphasizes that ARTs are not merely productivity tools but strategic instruments for resilient, efficient and sustainable livestock systems. The insights provided can guide veterinarians, breeders and policymakers in optimizing ART application, advancing global food security, and conserving valuable genetic resources.

Keywords: Assisted reproductive technologies; Livestock reproduction, Multiple ovulation and embryo transfer (MOET); In vitro fertilization (IVF); Precision livestock farming.

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Introduction

Reproductive efficiency is the cornerstone of profitable and sustainable livestock production. Across dairy, beef, sheep, goat and swine production systems, fertility determines parturition interval, replacement rates, lifetime output, milk yield and ultimately economic viability. Even marginal declines in reproductive performance translate into substantial financial losses at herd and industry levels. Consequently, optimization of fertility has long been a central objective of veterinary medicine and animal production sciences.

Natural mating, while biologically sufficient, imposes inherent constraints. Genetic dissemination in natural mating is slow and geographically limited (Halaweh *et al*., 2025). Disease transmission risks increase through direct animal contact. Selection intensity remains restricted to the reproductive capacity of individual males and females. Moreover, modern production systems demand structured breeding schedules that align with market cycles, labour management and nutritional planning; requirements not always compatible with uncontrolled reproductive timing.

Assisted reproductive technologies (ARTs) emerged to address these limitations. The development of artificial insemination in the early twentieth century marked the first major technological intervention in livestock reproduction (Ombelet and Robays, 2015). It enabled widespread dissemination of elite male genetics without physical animal movement. Over subsequent decades, advances in reproductive endocrinology, cryobiology, ultrasonography, embryo manipulation and molecular genetics expanded the technological repertoire far beyond semen deposition (Alberio, 2025).

Today, ARTs encompass synchronized breeding programs, superovulation, embryo recovery and transfer, in vitro embryo production, genomic-based selection, sex determination technologies, and gene editing platforms (Menchaca, 2023). These tools allow veterinarians and producers to strategically manipulate reproductive physiology, intensify selection pressure, shorten generation intervals and preserve valuable genetic resources.

Importantly, the contemporary role of ART extends beyond productivity enhancement. It intersects with food security, climate adaptation, biodiversity conservation and global trade. However, technological sophistication must be matched by biological precision, biosecurity vigilance, welfare oversight and ethical governance. Therefore, this review synthesized the biological foundations, technological advancements and practical applications of assisted reproductive technologies in livestock production. It further examined biosecurity considerations, precision integration with digital monitoring, and economic, ethical and welfare dimensions, highlighting the role of ART as a strategic tool for sustainable and resilient livestock systems. To fully appreciate the operational potential of ART, one must first understand the physiological framework upon which all reproductive manipulation is based.

Physiological Basis of Reproduction in Livestock

Reproduction in livestock is governed by intricate endocrine networks, tightly regulated cellular processes and species-specific physiological patterns. A detailed understanding of these mechanisms is fundamental to the effective application of ART. The hypothalamic-pituitary-gonadal (HPG) axis orchestrates gametogenesis, oestrous cyclicity, fertilization and early embryonic development, providing defined intervention points for hormonal manipulation, synchronization and embryo management (Acevedo-Rodriguez *et al*., 2018). Reproductive physiology varies across species, influencing the design and efficacy of ART protocols, and forms the biological foundation upon which modern breeding strategies are built.

Hypothalamic–Pituitary Regulation: The hypothalamic–pituitary axis serves as the primary regulatory hub of reproduction. Gonadotropin-releasing hormone (GnRH), secreted in a pulsatile pattern from the hypothalamus, stimulates the anterior pituitary to release follicle-stimulating hormone (FSH) and luteinizing hormone (LH) (Hassanein et al., 2024). The FSH promotes follicular recruitment, granulosa cell proliferation and Sertoli cell support of spermatogenesis, whereas LH triggers ovulation in females and stimulates Leydig cells to produce testosterone in males (Santi et al., 2020). Feedback loops involving oestradiol, inhibin, and progesterone modulate GnRH and gonadotropin secretion, ensuring synchronized reproductive events **(**Messinis, 2006)**.**

Endocrine responsiveness is highly sensitive to internal and external factors, including nutrition, metabolic status, stress, and photoperiod. Disruptions in GnRH pulsatility or pituitary responsiveness can delay ovulation, impair gametogenesis, and compromise fertility (Tsutsumi and Webster, 2009). Understanding these dynamics allows precise timing of ART interventions, including hormonal synchronization, timed artificial insemination and superovulation, enhancing conception rates and reproductive efficiency. Moreover, advances in reproductive endocrinology have enabled targeted modulation of these pathways, facilitating integration with embryo-based technologies and genomic selection.

Ovarian Follicular Dynamics: Female fertility is driven by cyclic ovarian activity, which is characterized by the coordinated growth and regression of follicular waves. Each cycle involves recruitment of a cohort of antral follicles, selection of a dominant follicle and atresia of subordinate follicles. Oestradiol produced by the dominant follicle induces behavioural oestrus and triggers the pre-ovulatory LH surge, culminating in ovulation (Chauvin et al., 2022). Following ovulation, the corpus luteum forms and secretes progesterone to prepare the uterus for implantation and maintain early pregnancy. In the absence of fertilization, prostaglandin $F_2\alpha$ induces luteolysis, resetting the cycle.

Follicular dynamics vary among species. Cattle exhibit predictable two- or three-wave cycles that facilitate synchronization programs, while small ruminants demonstrate seasonal breeding patterns influenced by photoperiod and melatonin secretion (Kolachi *et al.*, 2025). Swine have shorter cycles with multiple ovulations per oestrus, requiring precise timing for insemination. Nutritional status, age, stress and health status influence follicular responsiveness, ovulation rate and oocyte quality. Detailed understanding of these mechanisms underpins superovulation protocols, timed artificial insemination, ovum pick-up and embryo transfer procedures, ensuring optimal alignment between physiological readiness and ART application.

Male Reproductive Physiology: Male reproductive function is central to fertilization success and overall herd reproductive efficiency. Spermatogenesis occurs in the seminiferous tubules and is regulated by FSH, which supports Sertoli cell function, and LH, which stimulates Leydig cell testosterone production (Santi *et al*., 2020). Testosterone is essential for sperm maturation, secondary sexual characteristics and libido. Epididymal maturation imparts motility, membrane stability and fertilizing competence, which are critical for semen collection, processing, and cryopreservation (James *et al*., 2020).

Semen quality is influenced by intrinsic factors such as age, breed and genetics, and by extrinsic factors including nutrition, heat stress and disease. Cryopreservation introduces additional challenges, as sperm are susceptible to osmotic stress and membrane damage, with species-specific differences in cryotolerance influencing protocol design. For example, bovine sperm tolerate freezing well, whereas porcine sperm are highly sensitive and often require fresh or chilled semen for optimal fertility. Understanding these physiological nuances ensures successful artificial insemination (AI), in vitro fertilization (IVF), and multiple ovulation and embryo transfer (MOET) programmes, aligning reproductive management with male gamete biology.

Species-Specific Reproductive Dynamics and ART Implications

Reproductive physiology exhibits significant species-specific variation that directly informs ART strategies. Cattle are polyoestrous with well-defined follicular waves, making them highly amenable to timed AI, superovulation and non-surgical embryo recovery (Harl *et al*., 2025). Dairy breeds may experience metabolic stress or heat load that alter endocrine function and reduce their conception rates. Sheep and goats often exhibit seasonal breeding regulated by photoperiod and melatonin, requiring hormonal priming to initiate ovulatory cycles (Mapletoft *et al.,* 2018). Cervical anatomy and surgical considerations complicate insemination and embryo recovery in small ruminants.

Swine are polyovulatory with short cycles, demanding precise timing for AI and careful semen handling due to cryosensitivity (Bortolozzo *et al.,* 2024). Water buffalo and other species present delayed puberty, prolonged postpartum anoestrus, or weak oestrous expression, necessitating more intensive hormonal control. These interspecies differences dictate the design of superovulation protocols, timing of insemination, embryo collection methods and culture conditions for IVF. Recognizing and adapting to these physiological nuances is critical for maximizing ART efficiency, ensuring successful fertilization and achieving predictable reproductive outcomes across diverse livestock systems. The physiological intervention points exploited by ART, GnRH administration, FSH superovulation, prostaglandin-induced luteolysis, timed insemination, and embryo transfer, are summarized in Figure 1.

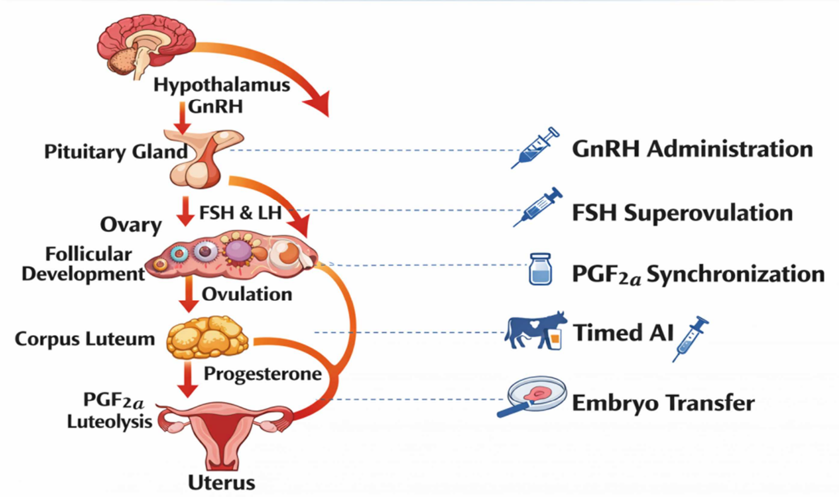

Figure 1. Intervention points for endocrine regulation of reproduction and assisted reproductive technology (ART).

Artificial Insemination

Building upon the physiological framework of endocrine regulation, artificial insemination (AI) represents the first and most transformative assisted reproductive technology in livestock production. By decoupling semen deposition from natural mating, AI allows precise control over genetic dissemination, disease management and reproductive scheduling. Its development marked the transition from passive breeding management to active reproductive engineering.

The biological premise of AI is simple: viable spermatozoa must be deposited within the female reproductive tract at an optimal interval relative to ovulation. However, successful implementation requires mastery of semen biology, oestrous synchronization and uterine physiology. Semen collection techniques, most commonly artificial vagina in cattle and small ruminants, and manual collection in swine, must preserve sperm viability and minimize contamination. Following collection, semen undergoes rigorous evaluation for concentration, progressive motility, morphology, membrane integrity and functional competence. These parameters directly influence fertilization success and serve as predictors of field fertility.

Cryopreservation constitutes one of the most significant scientific breakthroughs underpinning AI. The use of cryoprotectants and controlled freezing protocols permits long-term storage of semen at ultra-low temperatures, enabling global exchange of elite genetics and preservation of valuable germplasm (Roque-Borda *et al.*, 2021). Nevertheless, cryoinjury remains a biological limitation, as osmotic stress and ice crystal formation disrupt sperm membranes and mitochondrial function (Ozimic *et al.*, 2023). Species-specific variation in sperm cryotolerance explains why frozen semen performs reliably in cattle but remains less efficient in swine.

Oestrus detection has historically been a limiting factor in AI programs. Behavioural observation, although foundational, is labour-intensive and prone to human error. Hormonal synchronization protocols using GnRH, prostaglandins and progesterone-releasing devices have revolutionized reproductive scheduling by allowing fixed-time AI independent of visual oestrus detection. These protocols synchronize follicular wave emergence and ovulation, aligning insemination with peak fertility windows.

Beyond genetic acceleration, AI significantly reduces transmission of venereal pathogens by eliminating direct animal contact. It also enhances farm safety by reducing the need to maintain breeding males. In intensive dairy systems, AI has enabled sustained genetic gain in milk production, feed efficiency and disease resistance over successive generations.

Despite its maturity as a technology, AI remains sensitive to management quality. Nutritional deficits, metabolic stress, heat load, improper semen handling and suboptimal insemination technique can all depress conception rates. Thus, AI exemplifies the intersection of biological precision and managerial discipline. Its success laid the groundwork for more complex embryo-based and molecular reproduction technologies, which extend genetic amplification beyond the male line to the elite female population.

Multiple Ovulation and Embryo Transfer

While artificial insemination revolutionized dissemination of superior male genetics, it did not proportionally expand the reproductive contribution of elite females, which remained biologically constrained to producing a limited number of offspring over their lifetime. Multiple ovulation and embryo transfer (MOET) was developed to overcome this limitation by biologically amplifying the genetic influence of high-merit donor females (King *et al.,* 2022). Through controlled ovarian hyperstimulation and embryo recovery, MOET transforms a single oestrous cycle into an opportunity for multiple pregnancies across synchronized recipients (King *et al.,* 2022).

The biological foundation of MOET lies in manipulation of follicular dynamics. Administration of exogenous FSH stimulates recruitment and maturation of multiple dominant follicles rather than the single ovulation characteristic of a natural cycle. Synchronization with prostaglandin-induced luteolysis ensures coordinated oestrus and ovulation timing (Cguang *et al*., 2025). Following insemination, often performed multiple times within the same oestrous period to maximize fertilization probability, embryos are allowed to develop in vivo to the morula or early blastocyst stage before recovery. Embryo collection is typically performed approximately seven days post-oestrus in cattle using non-surgical trans-cervical uterine flushing. The procedure requires careful control of uterine tone, catheter placement and sterile technique to prevent contamination and maximize recovery rates. In small ruminants, anatomical constraints frequently necessitate laparoscopic or surgical recovery methods, which increase procedural complexity. Retrieved embryos are evaluated microscopically for developmental stage and morphological quality before being selected for fresh transfer or cryopreservation.

The success of MOET is highly dependent on synchronization precision between donor and recipient. The uterine environment of the recipient must closely match the developmental stage of the transferred embryo to support implantation and luteal maintenance. Pregnancy rates are influenced by donor response variability, embryo quality, recipient health and environmental stressors. Super-ovulatory response itself is notoriously inconsistent, varying with breed, age, nutritional status, ovarian reserve and endocrine sensitivity. Repeated stimulation may reduce ovarian responsiveness over time.

MOET has substantially accelerated genetic gain in dairy and beef industries by reducing generation intervals and multiplying high-merit female lineages (Granleese *et al.,* 2015; Campolina *et al*., 2022). When integrated with genomic selection, it allows identification and rapid propagation of superior genotypes early in life. However, the technology is resource-intensive, requiring hormonal inputs, skilled personnel and structured herd management. Welfare considerations related to repeated hormonal stimulation and invasive procedures must also be addressed through careful veterinary oversight.

By expanding reproductive output beyond natural biological limits, MOET represents the first major step toward comprehensive embryo-based genetic management. Its limitations in super-ovulatory variability and in vivo dependency paved the way for laboratory-based fertilization systems, which further decoupled reproduction from physiological constraints. A comparison of AI, MOET, IVF, sex-sorting, cloning and cryopreservation is presented Table 1.

In-vitro Fertilization and In-vitro Embryo Production

While MOET amplifies the reproductive contribution of elite females in vivo, it is constrained by donor physiology, environmental stressors and variability in super-ovulatory response. In vitro fertilization (IVF) and in vitro embryo production (IVP) were developed to overcome these limitations by relocating fertilization and early embryogenesis into controlled laboratory environments, enabling precise manipulation of gametes and embryos independent of natural uterine constraints (Mikkaola *et al.,* 2024).

Table 1. Comparative summary of assisted reproductive technologies (ART) in livestock production.

ART Method	Biological / Physiological Basis	Procedure / Technique	Applications	Advantages	Limitations / Challenges
Artificial Insemination (AI)	Sperm deposition timed to ovulation; relies on oestrous cycle and HPG axis	Collection, evaluation, processing, and deposition of semen into female reproductive tract; natural or timed AI protocols	Dairy, beef, swine, and small ruminant breeding; genetic improvement	Rapid dissemination of superior genetics; disease control; safer than natural mating	Requires oestrus detection or synchronization; semen handling critical; conception rates affected by stress and nutrition
Multiple Ovulation & Embryo Transfer (MOET)	Superovulation of donor female; uterine receptivity for embryo implantation	Hormonal stimulation (FSH/eCG), insemination, embryo recovery via uterine flushing / laparoscopy, grading, and transfer to recipients	Accelerated multiplication of elite or rare female genetics; breed improvement	Shortens generation interval; multiplies high-merit genetics; compatible with genomic selection	Variable superovulatory response; requires skilled labuor; cost-intensive; welfare concerns
In Vitro Fertilization (IVF) & In Vitro Embryo Production (IVP)	Oocyte maturation, fertilization, and early embryogenesis outside the body	Ovum pick-up (OPU), in vitro maturation (IVM), fertilization with capacitated sperm, embryo culture to blastocyst, transfer or cryopreservation	Genetic improvement, fertility management, valuable germplasm conservation	Enables use of subfertile donors; allows preimplantation genetic selection; integration with sexed semen	Lower pregnancy rates than in vivo embryos; expensive; technical expertise required; risk of developmental anomalies
Sex-Sorted Semen	Separation of X- and Y-bearing sperm to predetermine offspring sex	Flow cytometry-based sorting; AI using sorted semen	Dairy production and specific breeding programs	Predetermination of offspring sex; enhances herd management efficiency	Reduced conception rates; specialized equipment needed; cost-intensive
Cloning & Gene Editing (CRISPR-Cas)	Nuclear transfer or targeted genome modification to replicate or enhance traits	Somatic cell nuclear transfer, embryo culture, gene-editing in zygotes	Replication of elite animals; introduction of desired traits	Preserves elite genetics; enables trait-specific improvement; supports research	High cost; low efficiency; ethical and regulatory concerns; welfare implications
Cryopreservation	Freezing of gametes or embryos for long-term storage	Controlled-rate freezing or vitrification; storage in liquid nitrogen	Long-term germplasm conservation; global supply of genetics	Enables international germplasm exchange; supports breed conservation	Cryoinjury risks; requires laboratory infrastructure and expertise

The process begins with ovum pick-up (OPU), a minimally invasive, ultrasound-guided aspiration of immature oocytes from ovarian follicles. OPU allows repeated collection from high-value donors, including pregnant or prepubertal animals, without inducing hormonal superovulation in every cycle. Retrieved oocytes undergo in vitro maturation (IVM) in specialized culture media that replicate the biochemical milieu of the oviduct, providing essential nutrients, growth factors and hormonal support for meiotic completion and cytoplasmic maturation.

Following maturation, capacitated sperm are introduced to achieve fertilization. Capacitation, a series of functional and biochemical changes that render spermatozoa capable of penetrating the oocyte, can be induced in vitro through chemical or protein-mediated protocols (Ickowicz *et al.,* 2012). Successful zygotes are then cultured under precisely controlled conditions to reach the morula or blastocyst stage. Embryo development is carefully monitored for morphological quality and viability prior to transfer or cryopreservation.

IVF offers strategic advantages over MOET and AI. It enables rapid multiplication of elite female genetics regardless of in vivo ovulatory variability, facilitates pre-implantation genetic testing, and integrates seamlessly with sex-sorted semen technologies to predetermine offspring sex. IVF is particularly valuable in breeds with poor super-ovulatory response or in animals affected by subfertility, extending the utility of high-merit genetics beyond physiological limits (Gudapati *et al*., 2024).

However, IVP presents its own challenges. Pregnancy rates following transfer of in vitro-produced embryos are often lower than those derived in vivo, reflecting subtle differences in epigenetic regulation, cytoplasmic maturation, and early embryonic metabolism (Seneda *et al*., 2024; Neufeld *et al.,* 2026). Developmental abnormalities, such as Large Offspring Syndrome, have been reported under suboptimal culture conditions (Heras *et al*., 2016). Moreover, laboratory infrastructure, technical expertise and operational costs remain significant barriers to large-scale adoption, particularly in resource-limited systems. Despite these limitations, IVF has become a cornerstone of modern reproductive programs, enabling integration of genomic selection and precise genetic management. By decoupling reproduction from the physiological constraints of donor females, IVF and IVP allow unprecedented control over genetic propagation, supporting both intensive breeding programs and conservation efforts for endangered or rare breeds. This technological leap paved the way for advanced reproductive biotechnologies, including cloning, gene editing and precision selection, which now extend the scope of genetic intervention to the molecular level.

Emerging and Advanced Reproductive Biotechnologies

Beyond traditional gamete and embryo manipulation, emerging reproductive biotechnologies now integrate molecular genetics, cellular engineering and precision breeding strategies to enhance reproductive efficiency, accelerate genetic gain, and broadening the scope of livestock improvement. These innovations represent a paradigm shift, moving assisted reproduction from a primarily physiological intervention to a highly informed, data-driven and molecularly guided practice.

Genomic selection has emerged as a transformative tool in this context. By analysing dense panels of single nucleotide polymorphisms across the genome, breeders can estimate the genetic merit of animals at an early age, long before phenotypic performance is observable (Lee *at al*., 2024). When combined with ART platforms such as IVF and MOET, genomic data allow selection of superior embryos or donor females prior to implantation, effectively shortening generation intervals and maximizing the efficiency of breeding programs (Lee *at al*., 2024). This integration enables simultaneous optimization for multiple traits, including milk yield, feed efficiency, disease resistance and reproductive fitness.

Sex-sorted semen represents another major advancement. Using flow cytometry to separate X- and Y-chromosome-bearing sperm, producers can predetermine the sex of offspring, a particularly valuable capability in dairy systems that prioritize female replacements. Although conception rates using sexed semen are generally slightly lower than conventional semen, continuous improvements in sorting accuracy, sperm handling and insemination timing have enhanced field outcomes, making sex determination a reliable tool for herd management.

Cloning through somatic cell nuclear transfer (SCNT) allows the replication of elite or rare animals, providing a mechanism to preserve superior genotypes and propagate desired traits rapidly (Tian *et al*., 2003). While the efficiency of SCNT remains limited and operational costs high, cloning has critical applications in research, conservation and the preservation of endangered breeds. Complementing cloning, gene-editing technologies, particularly CRISPR-Cas systems, now enable precise, targeted modifications of the genome (Ebrahimi *et al.,* 2023). These tools offer the potential to introduce traits such as disease resistance, environmental adaptability or enhanced production characteristics, while retaining the overall genetic integrity of the breed.

Advances in cryobiology and vitrification further support the integration of ART and molecular selection. Optimized freezing protocols now allow high survival rates of oocytes and embryos during long-term storage, facilitating international exchange of germplasm and long-term conservation of valuable genetic resources (Tharasanit and Thuwanut,, 2021). The combination of precise genomic selection, sexed semen, cloning and cryopreservation represents a fully integrated reproductive technology ecosystem.

Despite the immense promise of these innovations, they also introduce ethical, regulatory and welfare considerations. The manipulation of genetic material, the creation of cloned or gene-edited animals, and the global transfer of germplasm must be governed by strict biosafety frameworks, societal oversight and transparent ethical review. Adoption remains limited in many production systems due to cost, infrastructure and technical expertise requirements. Nevertheless, these advanced biotechnologies are reshaping the boundaries of reproductive science, redefining breeding strategies and expanding the potential of ART well beyond conventional approaches.

Biosecurity and Reproductive Diseases Risk in ART Programs

The expansion of assisted reproductive technologies has fundamentally altered patterns of pathogen transmission in livestock systems. While ART enables controlled genetic dissemination, semen, oocytes and embryos can serve as vectors for bacterial, viral and protozoal pathogens if proper sanitary and biosecurity measures are not maintained. Sub-clinical infections in donor animals, contaminated collection equipment or improper handling during in vitro procedures can compromise herd health and reproductive outcomes.

Semen processing incorporates multiple safeguards, including donor health screening, antibiotic extenders and cryogenic storage under controlled conditions. Embryo transfer is inherently safer due to the protective barrier of the zona pellucida and standardized washing protocols. Nevertheless, lapses in laboratory hygiene, culture media sterility or cryostorage integrity can undermine these defences. The global movement of germplasm further elevates the risk of trans-boundary pathogen dissemination, highlighting the need for harmonized sanitary standards and traceability systems (Kumar *et al.*, 2021).

Laboratory infrastructure, staff training and procedural compliance are central to minimizing biosecurity risks. Closed-system cryostorage, validated embryo washing techniques and rigorous screening of donors and recipients reduce the likelihood of contamination. Real-time monitoring of storage conditions and environmental controls within IVF laboratories reinforce these safeguards. Moreover, adherence to international guidelines for germplasm transport, certification and pathogen testing ensures that reproductive technologies do not inadvertently facilitate disease spread. The integration of biosecurity measures with ART is not merely technical but strategic. By systematically identifying potential contamination points and implementing preventive protocols, reproductive programs safeguard both genetic investment and herd health. Table 2 summarizes major ART components, associated pathogen risks and recommended mitigation strategies.

Effective biosecurity ensures that the benefits of ART (accelerated genetic gain, fertility optimization and conservation of elite lines) are realized without compromising animal health or international trade standards. It underscores the necessity of embedding reproductive technologies within robust veterinary oversight frameworks, balancing productivity with safety and sustainability.

Precision Livestock Farming and Digital Integration

The integration of assisted reproductive technologies with precision livestock farming represents a transformative advancement in reproductive management. Traditional oestrus detection methods, reliant on behavioural observation, are labour-intensive, error-prone, and are often inadequate in large or extensive herds. Sensor-based technologies, including activity monitors, rumination trackers, intravaginal temperature probes and automated oestrus detection devices, provide continuous, objective and real-time monitoring of reproductive status. By capturing subtle physiological and behavioural indicators, these systems enhance timing accuracy for artificial insemination, embryo transfer and ovum pick-up, ultimately improving conception rates and reproductive efficiency.

Table 2. Biosecurity risks and mitigation strategies across assisted reproductive technologies (ART).

ART Component	Potential Risk	Mechanism of Transmission	Mitigation Strategy	System Level Impact
Semen Collection	Venereal pathogens.	Contaminated ejaculate.	Donor screening, antibiotic extenders.	Reduced herd infection risk.
Embryo Culture	Laboratory contamination.	Media or equipment contamination.	Sterile handling, validated washing.	Improved embryo safety.
Cryostorage	Cross-contamination.	Shared nitrogen tanks.	Closed-system storage.	Secure germplasm preservation.
International Germplasm Trade	Emerging pathogens.	Transboundary movement.	Certification, traceability systems.	Global biosecurity compliance.

Data analytics and machine learning further amplify the utility of digital integration. Algorithms can predict ovulation, super ovulatory response and embryo viability by analysing multi-dimensional data streams encompassing hormonal profiles, environmental conditions and historical reproductive performance. These predictive models enable individualized reproductive interventions, allowing precise alignment of ART protocols with each animal's unique physiological state. The approach reduces reliance on generalized schedules and mitigates the risk of failed conception due to mistimed procedures.

Digital systems also enhance operational efficiency and biosecurity. Automated record-keeping ensures accurate tracking of semen usage, donor and recipient pairing, hormonal treatments and embryo transfers. Integration with herd health monitoring systems provides early detection of reproductive disorders, metabolic stress or disease outbreaks, enabling timely veterinary intervention. Coupled with stringent laboratory protocols, digital oversight reinforces biosecurity, supporting safe germplasm handling and storage.

The combined application of ART and precision livestock farming is conceptually illustrated in Figure 2, which depicts the flow from genomics-driven donor selection through IVF or MOET procedures, embryo evaluation, recipient synchronization and pregnancy outcome monitoring, all integrated with sensor technologies, welfare oversight and biosecurity controls. This systems-level framework highlights how reproductive biotechnologies can be strategically deployed to maximize efficiency, safeguard animal welfare and ensure sustainability.

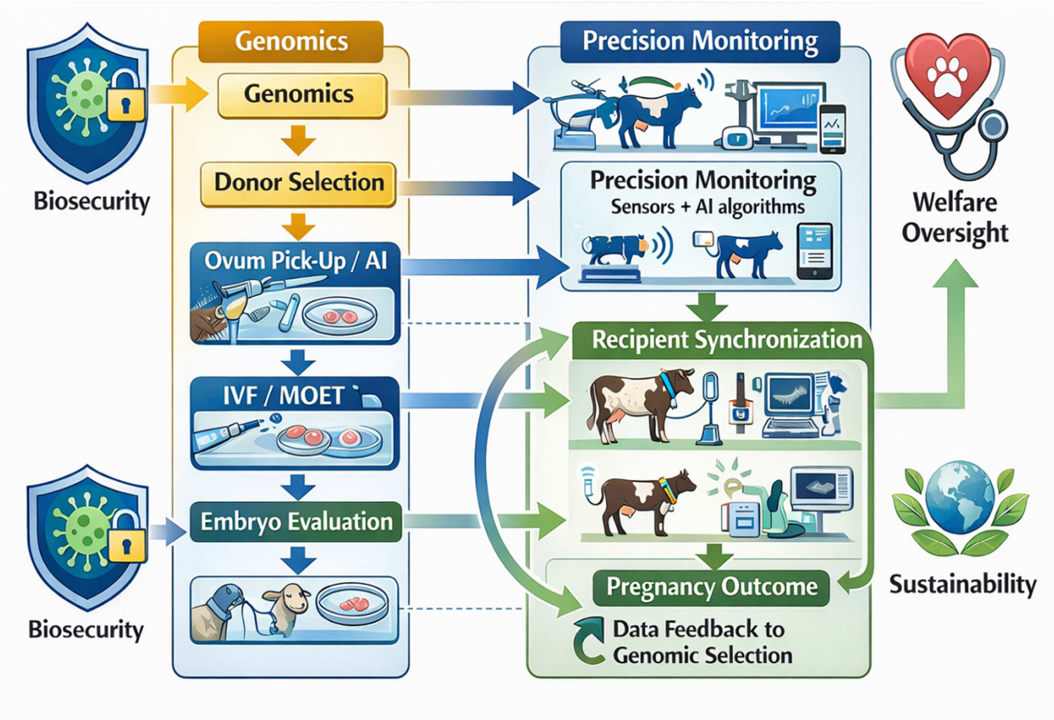

Figure 2. Integrated assisted reproductive technology (ART) framework in modern livestock production systems.

By transforming reproductive management into a data-informed, proactive practice, digital integration bridges biological knowledge, technological capability and operational management, enabling reproductive programmes that are more precise, productive and resilient than conventional approaches.

Global Adoption, Economic, Ethical and Welfare Dimensions of ART

The adoption and impact of assisted reproductive technologies vary widely across production systems and geographical regions, reflecting differences in infrastructure, economic resources, technical expertise and cultural acceptance. In high-input dairy and beef operations, ARTs are deeply integrated into structured genetic improvement programs, with artificial insemination, MOET and IVF routinely employed to accelerate genetic gain, optimize herd productivity and manage reproductive schedules. In contrast, smallholder and pastoral systems often face significant barriers to adoption, including limited access to trained personnel, prohibitive costs of hormonal treatments and laboratory facilities, and inadequate cold-chain infrastructure for semen or embryos. Despite these constraints, the potential for ARTs to enhance food security, breed improvement and climate resilience in low- and middle-income regions remains substantial, particularly when combined with cooperative breeding models, mobile veterinary services and community-based genetic resource management.

Economically, ARTs offer the prospect of substantial returns through improved milk yield, carcass quality, feed efficiency and disease resistance. By enabling rapid multiplication of elite genetics, these technologies shorten generational intervals and increase lifetime productivity. However, initial investment costs for infrastructure, technical expertise, hormonal protocols and laboratory facilities can be significant, particularly for advanced platforms such as IVF, embryo transfer or cloning. Cost-benefit outcomes are therefore highly context-dependent, and careful planning is required to ensure sustainability and scalability in diverse production systems.

Ethical and animal welfare considerations are increasingly central to ART deployment. Procedures involving repeated superovulation, ovum pick-up and embryo manipulation raise questions regarding animal stress, long-term reproductive health and ethical acceptability. Advanced technologies such as cloning and gene editing further provoke societal debate on genetic integrity, biodiversity conservation and the responsible use of biotechnology. Transparency, regulatory oversight and adherence to established welfare standards are essential to maintaining public trust and ensuring that reproductive innovations do not compromise animal well-being.

Sustainability considerations extend beyond economic and welfare concerns. Integration of ARTs with precision livestock farming, biosecurity protocols and environmentally responsible breeding strategies support resilient production systems. By facilitating the propagation of disease-resistant or climate-adapted genotypes, ART contributes to ecological sustainability while optimizing resource use. Furthermore, germplasm conservation via cryopreservation and targeted breeding supports biodiversity, safeguarding valuable genetic resources for future generations.

In summary, ARTs are not merely productivity tools but strategic instruments for enhancing herd genetics, reproductive efficiency and system resilience. Their adoption requires balancing economic investment, ethical responsibility, animal welfare and sustainability goals to ensure that the benefits of modern reproductive technologies are realized across diverse livestock production contexts.

Conclusion

Assisted reproductive technologies have evolved from simple semen deposition techniques into integrated, physiologically informed and digitally enhanced reproductive systems that shape modern livestock production. By strategically manipulating endocrine function, amplifying elite genetics and integrating genomic and precision monitoring tools, ARTs accelerate genetic gain while improving reproductive efficiency and disease control. Their success, however, depends on rigorous biosecurity, ethical oversight, animal welfare safeguards and context-specific economic planning. When embedded within sustainable management frameworks, ARTs extend beyond productivity enhancement to support climate resilience, biodiversity conservation and long-term herd health. Responsible integration of biological knowledge, technological innovation and veterinary governance will determine the future impact of assisted reproduction in global livestock systems.

Conflict of Interest

The author declare no conflict of interest.

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