Review Report

Integration of genomic selection and assisted embryo technologies for precision cattle breeding: opportunities, challenges and global perspectives

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Abstract

Modern cattle breeding increasingly integrates genomic selection (GS) with assisted reproductive technologies (ARTs) to accelerate genetic gain and enhance herd productivity. This review examines the synergistic application of GS and embryo-based technologies in dairy and beef cattle, and evaluates their potential to support precision breeding strategies. Relevant literature on genomic evaluation, embryo technologies and embryo-based breeding programs was synthesized to summarize current developments, opportunities, challenges, and global adoption patterns. ARTs, including artificial insemination, multiple ovulation and embryo transfer, in vitro embryo production, ovum pick-up, cryopreservation, and embryo biopsy, facilitate rapid multiplication of elite genetics and enable preimplantation selection. When combined with GS, these technologies allow estimation of genomic breeding values at early developmental stages, thereby reducing generation intervals, increasing selection intensity and improving the rate of genetic gain. Integrated breeding programs can also support targeted improvement of economically important traits (e.g. fertility, disease resistance, feed efficiency, production performance). Despite these advantages, practical implementation requires consideration of economic costs, technical expertise, infrastructure, recipient availability, and strategies to manage inbreeding and maintain genetic diversity. Global adoption varies considerably; highly integrated genomic and embryo-based breeding systems are well established in some countries (e.g. US, Australia) whereas emerging applications in regions including India, China, Brazil and Pakistan reflect varying levels of technological capacity and industry development. Emerging and developing approaches, including genome editing, artificial intelligence-assisted embryo evaluation and noninvasive embryo selection, together with continued improvements in established genomic prediction systems, are expected to further enhance precision breeding. Overall, integration of GS and ARTs represents a transformative approach for accelerating sustainable genetic improvement in cattle while supporting efficient and responsible breeding programs.

Keywords: Genomic selection, embryo transfer, in vitro embryo production, ovum pick-up, genomic breeding values, precision livestock breeding

Introduction

Cattle breeding has undergone profound transformation over the past several decades, driven by advances in reproductive technologies and genomic science.[1,2] Historically, genetic improvement relied primarily on phenotypic selection, in which animals were chosen as breeding candidates based on traits (e.g. milk yield, growth rate, body conformation, reproductive performance). Although this approach established the foundation for early genetic progress, it is inherently slow and imprecise. Phenotypic performance is influenced by both genetic and environmental factors, including nutrition, management, and climate, making accurate identification of superior genetics challenging.[3] In addition, the long generation interval, particularly in dairy systems, historically limited the rate of genetic improvement.

Development of quantitative genetics and pedigree-based estimated breeding values (EBVs) represented a major advancement in livestock breeding. These approaches enabled breeders to account for heritability and family relationships when making selection decisions.[4] However, accurate EBV estimation required comprehensive performance records and,

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in many cases, progeny testing, delaying selection decisions until animals reached maturity.[5] As global demand for animal protein increased and production systems faced growing pressure to improve efficiency, sustainability, and animal welfare, more advanced tools became necessary to accelerate genetic progress while maintaining selection accuracy.[6]

Modern cattle breeding programs now integrate advanced reproductive biotechnologies with GS, fundamentally reshaping strategies for genetic improvement.[1] Reproductive technologies, including artificial insemination (AI),[7] multiple ovulation and embryo transfer (MOET), in vitro embryo production (IVP),[8] and embryo biopsy,[9] enable increased reproductive output from genetically superior animals while allowing greater control over mating decisions. AI, the most widely adopted reproductive technology in cattle breeding, allows semen from elite sires to be distributed across large populations,[7] substantially increasing selection intensity on the male side. MOET and IVP extend similar advantages to elite females by enabling production of multiple offspring annually,[8] thereby overcoming the natural biological constraint of 1 calf per cow per year.

In parallel, advances in molecular genetics have enabled development of GS that uses dense panels of DNA markers, typically single nucleotide polymorphisms (SNPs), to estimate an animal's genetic merit.[10] Unlike traditional EBVs, genomic estimated breeding values (GEBVs) can be calculated early in life, often shortly after birth or even at the embryo stage.[11,12] This early prediction capability reduces generation intervals and improves selection accuracy, particularly for traits that are difficult or expensive to measure, including fertility, disease resistance, feed efficiency, and longevity.[9] In the US, key traits on which dairy and beef producers focus are in supplementary file 1 (What matters most: core traits driving US dairy and beef production).

Integration of embryo technologies with GS creates a powerful breeding strategy.[1,6] Embryo technologies increase the number of potential offspring from elite genetic lines, whereas GS enables precise identification of superior individuals within that expanded population.[13] Techniques (e.g. embryo biopsy, genotyping) allow selection decisions to occur prior to embryo transfer, ensuring that only embryos with the highest predicted genetic merit are implanted.[9] This approach maximizes genetic gain per generation while improving efficiency of breeding programs by reducing the number of lower-merit animals entering production systems.[6]

These technologies have had a particularly strong impact in dairy cattle breeding, where GS has largely replaced traditional progeny testing for young bulls and elite females.[5] Their application is also expanding rapidly in beef production systems as reference populations grow, genotyping costs decline, and interest increases in traits related to efficiency, meat quality and environmental sustainability.[13,14] By enabling earlier and more accurate selection for complex traits, embryo technologies and GS contribute to improved productivity, profitability and resilience in cattle populations.[1]

Despite their transformative potential, adoption of these technologies raises important practical, economic and ethical considerations.[1] High implementation costs,[13] technical expertise requirements[13] and concerns regarding genetic diversity and inbreeding[6] must be carefully managed to ensure long-term sustainability.[15] Nevertheless, continued technological advances and refinement of breeding strategies are expected to further expand the role of integrated reproductive and genomic technologies in modern cattle breeding. Together, these approaches enable faster genetic gain, greater precision in selection and more strategic use of genetic resources to meet the evolving demands of global livestock production.

Accordingly, the objective of this review is to critically examine the integration of genomic selection with assisted reproductive and embryo technologies in dairy and beef cattle breeding. Specifically, we summarize the biological and technological basis of GS–ART integration, evaluate its effects on selection accuracy, selection intensity, generation interval, and genetic gain, examine practical, economic, and genetic-diversity constraints, and discuss emerging applications, including beef-on-dairy systems and variation in adoption across global cattle industries. By integrating genomic and reproductive perspectives, this review aims to provide a practical framework for understanding how these complementary technologies can be used responsibly to accelerate genetic improvement while maintaining reproductive efficiency and long-term population sustainability.

Reproductive technologies in cattle

Embryo technologies have a central role in modern cattle breeding by overcoming natural reproductive limitations and enabling more intensive and precise genetic selection. By increasing reproductive output from genetically superior animals and allowing manipulation of embryos prior to implantation, these technologies substantially enhance the efficiency of breeding programs.[7,13,16] When integrated with genomic selection, embryo technologies are powerful tools for accelerating genetic gain while optimizing reproductive resources.[1] Key reproductive technologies used in cattle breeding include artificial insemination (AI), MOET, IVP combined with ovum pick-up (OPU), cryopreservation, and embryo biopsy for preimplantation genetic screening.

Artificial insemination

Artificial insemination is the most widely adopted reproductive technology in cattle breeding.[7] The procedure involves collection of semen from genetically superior bulls, followed by processing, cryopreservation, and distribution for insemination of cows across diverse herds and geographic regions.[7,15] AI revolutionized cattle breeding by allowing a single elite sire to produce thousands or even millions of offspring, far exceeding the reproductive capacity achievable through natural mating.[3]

The primary genetic advantage of AI is the substantial increase in male selection intensity.[3] Extensive use of top-performing bulls enables rapid dissemination of superior genetics across large populations. AI also improves reliability of genetic evaluation because semen from proven sires can be used across multiple herds and environments, generating more robust performance data.[7] In addition, AI enhances biosecurity by reducing animal movement and enabling greater control over mating decisions, thereby lowering risks of disease transmission.[7]

The impact of AI has been further amplified by genomic selection. Young bulls can now be selected and widely used based

on GEBVs, rather than waiting for progeny testing results.[11] This approach has markedly shortened generation intervals, particularly in dairy breeding programs, and has contributed to rapid genetic progress in economically important traits.[11]

Multiple ovulation and embryo transfer

Whereas AI primarily increases genetic contributions of elite males, MOET was developed to enhance selection intensity on the female side.[7,13] In this technique, donor cows are hormonally stimulated to induce multiple ovulation, resulting in release of multiple ova during a single estrous cycle.[16] These ova are fertilized through AI or natural mating and the resulting embryos are recovered from the uterus and transferred into synchronized recipient cows.[16]

Under natural conditions, a cow typically produces 1 calf per year, limiting propagation of superior female genetics.[7] However, MOET overcomes this constraint by enabling a single donor cow to produce multiple embryos annually, often yielding dozens of embryos across repeated collection cycles.[16] This approach substantially increases genetic contributions of elite females and expands the pool of related individuals available for selection.[13]

MOET has been widely adopted in nucleus breeding herds and pedigree operations where maximizing the genetic influence of high-value females is economically justified.[16] However, variability in ovarian superstimulatory response among cows and the need for hormonal treatments and specialized technical expertise can limit efficiency.[13,16] Despite these limitations, MOET remains an important tool, particularly when combined with genomic information to identify superior donors early in life.[1]

Ovum pick-up and in vitro embryo production

In vitro embryo production represents a major advancement in reproductive biotechnology, offering greater flexibility than MOET.[16] IVP involves several stages, including oocyte retrieval through OPU, in vitro maturation (IVM), in vitro fertilization (IVF), and in vitro embryo culture prior to transfer or cryopreservation.[13,16,17] OPU is a minimally invasive, ultrasound-guided procedure that enables repeated collection of oocytes directly from the ovaries.[13,17]

Unlike MOET, IVP does not depend on a donor's response to ovarian superstimulation protocols and can be performed more frequently, often at 2-week intervals.[13,16] This allows embryo production from a broader range of animals, including prepubertal heifers, pregnant cows, and animals that respond poorly to hormonal stimulation.[18] Consequently, IVP substantially increases the number of embryos that can be produced from genetically valuable females during their lifetime.[7,16]

IVP is particularly compatible with GS strategies.[1] Oocytes can be collected from genomically elite animals at a young age, allowing their genetic potential to be rapidly converted into offspring. Additionally, IVP enables the use of sex-sorted semen and precise sire-dam combinations, providing greater flexibility in breeding strategies. Integration of sex-sorted semen with IVP (and where applicable, MOET) further increases the ability to generate offspring of the desired sex. In dairy breeding programs, for example, preferential production of female offspring from elite donors can increase the supply of high-genetic-merit replacement heifers and further amplify the genetic impact of selected maternal lines.[13,19,20] Although IVP may be more expensive and technically demanding than conventional embryo transfer, its efficiency and adaptability have led to rapid adoption in both dairy and beef cattle industries.[7]

Cryopreservation and embryo transfer

Cryopreservation is an essential supporting technology that enables practical implementation of embryo-based breeding programs. Embryos produced through MOET or IVP can be preserved using advanced freezing techniques, particularly vitrification, which minimizes ice crystal formation and improves postthaw survival.[21,22] Cryopreserved embryos can be stored for extended intervals and transferred when suitable recipient cows become available or when specific breeding objectives arise.[16]

This capability enhances the flexibility of breeding programs by allowing synchronization of embryo availability with recipient readiness, facilitating long-term conservation of genetic resources, and enabling international exchange of genetic material without transporting live animals.[16] Cryopreservation also supports genomic selection strategies by allowing embryos to be genotyped and stored while selection decisions are made, ensuring that only embryos with the highest predicted genetic merit are transferred.[1]

Successful embryo transfer requires careful synchronization of recipient cows to ensure optimal uterine conditions for implantation.[7,16,23] Pregnancy success depends on embryo quality, recipient management and technical expertise, highlighting the importance of integrated reproductive management in advanced breeding systems.[7,16,24]

Embryo biopsy and preimplantation genetic screening

Embryo biopsy combined with preimplantation genetic screening represents one of the most recent advancements in bovine embryo technology.[25,26] Historically, one of the principal applications of embryo biopsy in cattle was embryo sex determination, allowing producers to select embryos of the desired sex before transfer. Although embryo biopsy is now less commonly performed solely for sex determination because of advances in sex-sorted semen and genomic technologies, embryo sexing represented an important early application of preimplantation testing and helped establish the technical foundation for contemporary embryo-level genomic evaluation. In this procedure, a small number of cells are removed from an early-stage embryo, typically at the blastocyst stage, without compromising developmental potential. DNA extracted from these cells is then genotyped to estimate the embryo's genomic breeding value.[27]

This approach enables selection decisions before pregnancy is established, a strategy commonly referred to as preimplantation genomic selection.[27] By transferring only embryos with superior genomic predictions, breeding programs can further increase selection intensity and efficiency while reducing the costs associated with raising lower-merit animals.[9]

Embryo biopsy also allows selection for specific traits (e.g. disease resistance or fertility, genomic information) can be integrated with sex-selection strategies to meet specific production objectives.[28] However, technical challenges remain, including maintaining genotyping accuracy from limited DNA samples and preserving embryo viability following biopsy.[29-31] As these methodologies improve and costs decline, embryo biopsy is expected to become an increasingly important component of elite cattle breeding programs.[1,25]

Key message

Embryo technologies have transformed cattle breeding by expanding reproductive capacity, increasing selection intensity and enabling greater control over genetic outcomes. From the widespread use of AI to advanced approaches (IVP, embryo biopsy technologies) provide the biological foundation upon which genomic selection can operate most effectively. When strategically integrated, embryo technologies allow breeders to rapidly identify, propagate and disseminate superior genetics, supporting development of efficient, sustainable and precision-based cattle production systems.

Genomic selection: game changer

GS represents a major advancement in cattle breeding by enabling prediction of an animal's genetic merit using genome-wide marker information. This approach relies on dense panels of genomic markers, most commonly thousands of SNPs, distributed across the genome.[10,32] These markers capture combined effects of many genes influencing economically important traits. By incorporating genomic data into breeding value estimation, GS enables calculation of GEBVs with substantially greater accuracy than traditional pedigree-based methods, particularly early in life.[10,12,32]

Practical implementation of GS began in the late 2000s, initially in dairy cattle and later expanding to beef systems.[10,11] Adoption was accelerated by declining genotyping costs and development of large reference populations containing both genomic and phenotypic records. Importantly, studies demonstrated that genomic information alone could provide prediction accuracies comparable to those obtained through extensive progeny testing.[14] This finding transformed breeding strategies by reducing reliance on time-consuming progeny testing and enabling selection decisions at much earlier ages.[1] A practical overview of major genomic application options for dairy and beef cattle in the US is provided in supplementary file 2 (Applied genomics in US cattle production: methods, tools, and decisions).

The advantages of GS are particularly pronounced when integrated with embryo technologies. One key benefit is improved selection accuracy in young animals, including embryos. Through embryo biopsy and genotyping, GEBVs can be estimated before embryo transfer, allowing embryos with the highest predicted genetic merit to be selected.[25,33] Early-stage selection ensures that only genetically superior embryos are transferred, increasing efficiency of embryo programs and reducing numbers of lower-merit animals entering production systems.[1,25,33]

Genomic selection also shortens generation intervals, especially when combined with embryo technologies (MOET, IVP).[1] Early identification of elite males and females allows these animals to be used as donors at a young age, while embryo technologies multiply their genetic contribution through rapid production of offspring.[11,14] The combined effects of reduced generation intervals and increased reproductive output markedly accelerate genetic gain.

Another major advantage of GS is increased selection intensity among females. Historically, female selection was constrained by lower accuracy and reproductive limitations. Genomic testing allows large numbers of heifers or embryos to be screened, after which embryo technologies can be applied selectively to the highest-ranking individuals.[33,34] This targeted strategy increases genetic contributions of elite females and aligns female selection intensity more closely with that of males (Figure 1).

Schematic workflow illustrating integration of genomic tools and reproductive biotechnologies used to accelerate genetic improvement in cattle populations. The process begins with genomic selection, where genome-wide DNA markers (e.g. SNPs) are used to identify genetically superior bulls and cows. Elite male genetics are disseminated through artificial insemination, enabling rapid genetic dissemination across herds. On the female side, MOET increases selection intensity by producing multiple embryos per reproductive cycle. Advanced laboratory-based embryo production through in vitro embryo production, combined with ovum pick-up, allows oocytes to be collected from genetically superior females and fertilized in vitro, enabling flexible and frequent embryo generation. Produced embryos may undergo embryo biopsy, followed by genomic testing, to identify individuals with the highest predicted genetic merit prior to transfer. Selected embryos can be preserved using embryo cryopreservation, facilitating long-term storage, international transport, and optimized transfer timing into recipient cows. Integration of these technologies produces genetically superior calves with improved performance traits, ultimately accelerating genetic gain and supporting sustainable cattle production worldwide.

GS also improves management of inbreeding by providing precise estimates of genomic relationships among animals.[35] These data can be incorporated into mating plans to balance genetic gain with maintenance of genetic diversity.[35]

Overall, integration of GS with embryo technologies represents a paradigm shift in cattle breeding. Genomic tools enable early identification of superior genetics, while reproductive technologies rapidly propagate those genetics across populations.[36] Together, they support a precision-based breeding strategy capable of accelerating genetic improvement for complex traits (e.g. fertility, disease resistance, feed efficiency) while promoting long-term sustainability of cattle production systems.

Synergies between embryo technologies and genomic selection

Integration of embryo technologies with GS is one of the most important advances in modern cattle breeding. Each approach independently improves genetic progress; however, their combined application creates synergistic effects that substantially increase the rate, accuracy and efficiency of selection.[37] Embryo technologies expand the number of potential offspring from genetically superior animals whereas GS enables precise

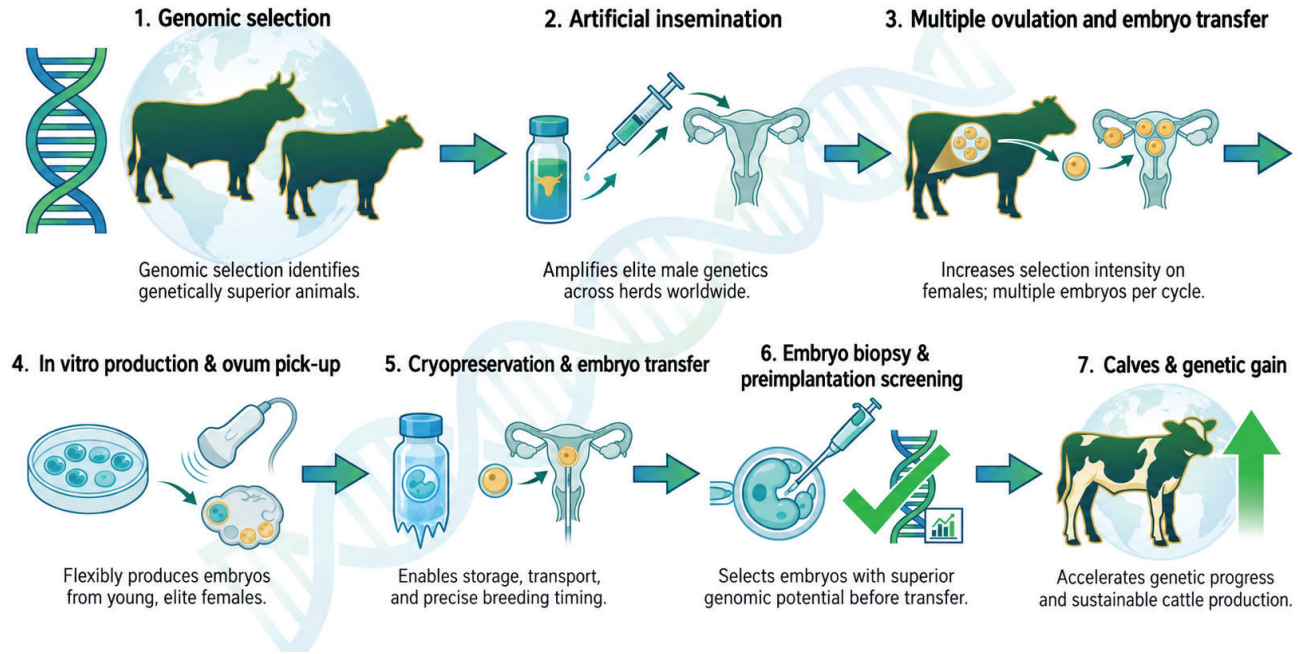


Figure 1. From genes to calves: integration of genomics and embryo technologies in cattle

identification of the most valuable individuals within that expanded pool.[38,39] Together, these technologies enable earlier selection, increased selection intensity, shorter generation intervals, improved control over reproductive and genetic outcomes.

Accelerating genetic gain

Genetic gain in breeding programs depends on selection accuracy, selection intensity, genetic variation and generation interval.[40-42] Integration of reproductive biotechnologies with GS can influence these components and thereby hasten the rate of genetic gain.[40-42] Embryo technologies (e.g. MOET, IVP) increase the number of embryos produced from elite parents,[41] creating a larger pool of candidates for genomic evaluation and stronger selection pressure.[37]

These effects can be conceptualized using the breeder's equation

$\Delta G = (i \times r \times \sigma A)/L$

where i is selection intensity
r is selection accuracy
σA is the additive genetic standard deviation
L is generation interval

GS–ART integration can influence several components simultaneously: genomic evaluation improves selection accuracy at young ages, screening larger numbers of animals or embryos increases selection intensity, and early selection combined with MOET or OPU–IVP can shorten generation intervals by enabling genetically superior animals to contribute offspring earlier and more frequently. Consequently, GS–ART integration can accelerate genetic gain through complementary effects on multiple components of the breeding equation. The magnitude of improvement is population and trait-dependent and varies with genomic-prediction accuracy, number of selection candidates, reproductive efficiency and constraints imposed to manage inbreeding.[42]

A major innovation arising from this integration is preimplantation genomic selection, in which embryos are genotyped before transfer. Through embryo biopsy and genomic evaluation, GEBVs can be estimated at very early developmental stages. Only embryos with the highest predicted genetic merit are transferred into recipient cows, ensuring that reproductive resources are concentrated on individuals with the greatest potential.

Preimplantation genomic selection also reduces economic and logistical costs associated with raising lower-merit animals.[27] By preventing genetically inferior embryos from entering production systems, breeders avoid expenses associated with pregnancy, rearing and long-term management.[41] This advantage is particularly relevant in dairy systems, where replacement rates and rearing costs are high.

Furthermore, IVP programs combined with genomic selection allow effective discrimination among full and half-sibling embryos. Traditionally, selection within families was limited because individual genetic merit among siblings could not be distinguished early in life.[38] Genomic information captures Mendelian sampling variation, enabling breeders to identify the best individuals within each family rather than relying solely on average parental merit.[43] This increased within-family selection intensity contributes significantly to accelerated genetic progress.

Selection of donors and recipients

GS enhances efficiency of embryo technologies by enabling early identification of superior donors and sires. Genomic testing allows elite animals to be identified at a young age, often before reaching reproductive maturity.[38] This early identification allows high-GEBV animals to enter embryo production programs sooner, reducing generation intervals and accelerating dissemination of desirable genetics.[44]

Selecting donors based on genomic merit increases the likelihood that embryos produced will have superior genetic potential, improving cost-effectiveness of MOET and IVP programs.[45] This is particularly important given the technical complexity and financial investment associated with embryo production.

Genomic information also supports optimized sire selection. By combining parental GEBVs, breeders can design mating strategies that maximize predicted progeny performance while managing inbreeding.[46] Because genomic data provide more accurate estimates of relatedness than pedigree records, mate allocation can be performed with greater precision.

Recipient selection may also benefit from genomic information. Although recipients do not contribute genetically to the calf, their reproductive performance strongly influences pregnancy success and calf survival. Genomic evaluations for fertility-related traits may help identify recipients with superior uterine environment, conception rates and maternal ability.[47,48] Selecting high-performing recipients can therefore improve embryo transfer success and overall reproductive efficiency.[33] Genomic applications using OPU technology in US dairy operations are described in supplementary file 3 (Precision breeding in action: OPU-IVF meets genomics).

Gender selection and specialized traits

Gender selection technologies integrate effectively with genomic selection and embryo technologies to refine breeding strategies. Modern techniques (e.g. sex-sorted semen, embryo sexing) allow producers to control offspring sex, according to production goals.[49] In dairy systems, female calves are typically preferred for herd replacement whereas male calves may be favored in beef systems for growth and carcass traits.

When combined with genomic selection, gender selection enables highly targeted breeding decisions. Female embryos with superior GEBVs for milk production and fertility can be prioritized for transfer whereas male embryos with desirable growth or carcass traits may be directed toward beef production.[33,50] Such strategies maximize the economic value of embryos generated through advanced reproductive technologies.

Conception rates using sex-sorted semen are generally lower than those achieved with conventional semen.[49] Integrating gender selection with genomic evaluation helps offset this limitation by ensuring that only embryos with high genetic merit are transferred.[50]

Genomic tools also enable targeted improvement of specialized traits (e.g. disease resistance, heat tolerance, feed efficiency).[51-53] Embryo technologies allow rapid dissemination of these traits across herds, enabling breeding programs to address specific environmental challenges and production objectives.

Optimizing reproductive efficiency

Reproductive efficiency is a critical determinant of profitability and sustainability in cattle production systems. Reproductive traits (e.g. conception rate, embryo yield, pregnancy maintenance) are complex and influenced by both genetic and environmental factors.[54,55] Historically, these traits have been difficult to improve through conventional selection, due to limited measurement accuracy and low heritability.[54-56]

Integration of GS with embryo technologies provides new opportunities to enhance reproductive performance. Genomic evaluations can identify animals with favorable reproductive characteristics, including oocyte quality, embryo developmental competence, and pregnancy success.[37] Selecting donors with superior genomic profiles for reproductive traits can improve success rates in MOET and IVP programs while reducing production costs.[56,57]

Genomic information may also help identify individuals with superior responses to superovulation protocols or higher oocyte yield in IVP systems.[58] Over time, this may result in cattle populations with improved reproductive robustness, benefiting both conventional and advanced breeding systems.

Additionally, genomic tools can help identify animals with reduced susceptibility to reproductive disorders, improving animal welfare and longevity.[59] Incorporating such traits into breeding objectives supports development of more resilient and sustainable cattle populations.

Key message

The synergy between embryo technologies and GS has transformed cattle breeding from a largely phenotype-based process into a precision-driven, data-intensive system.[33,37,59] Early identification of superior genetics combined with rapid propagation through reproductive technologies accelerates genetic gain while improving efficiency and sustainability. Modern strategies (e.g. preimplantation genomic selection, optimized donor and recipient selection, sex-controlled breeding and genomic improvement of reproductive traits) collectively represent a paradigm shift in cattle breeding (Figure 2).[59-61] As genomic tools and reproductive technologies continue to advance, their integration will remain central to the future of cattle breeding and global livestock production.

Conceptual diagram illustrating how genomic tools and reproductive biotechnologies interact to enhance efficiency of cattle breeding programs. Integration of genomic selection and embryo technologies results in production of genetically superior embryos. Additional strategies (e.g. sexed semen or sexed embryos) enable targeted production of offspring aligned with production goals whereas genomic information guides selection of both donors and recipients to maximize reproductive efficiency. Together, these synergistic approaches increase selection intensity, shorten generation intervals and accelerate genetic gain, resulting in healthier calves with improved traits (e.g. milk production, meat quality, fertility, disease resistance, feed efficiency) that support more sustainable cattle production systems.

Practical and economic considerations

Integration of GS with advanced embryo technologies offers substantial potential to accelerate genetic gain in cattle populations.[9,33,62] However, successful implementation requires careful consideration of practical, economic, and logistical factors.[42] Effectiveness of these technologies is influenced not only by biological constraints but also by infrastructure availability, operational expertise, and financial feasibility.

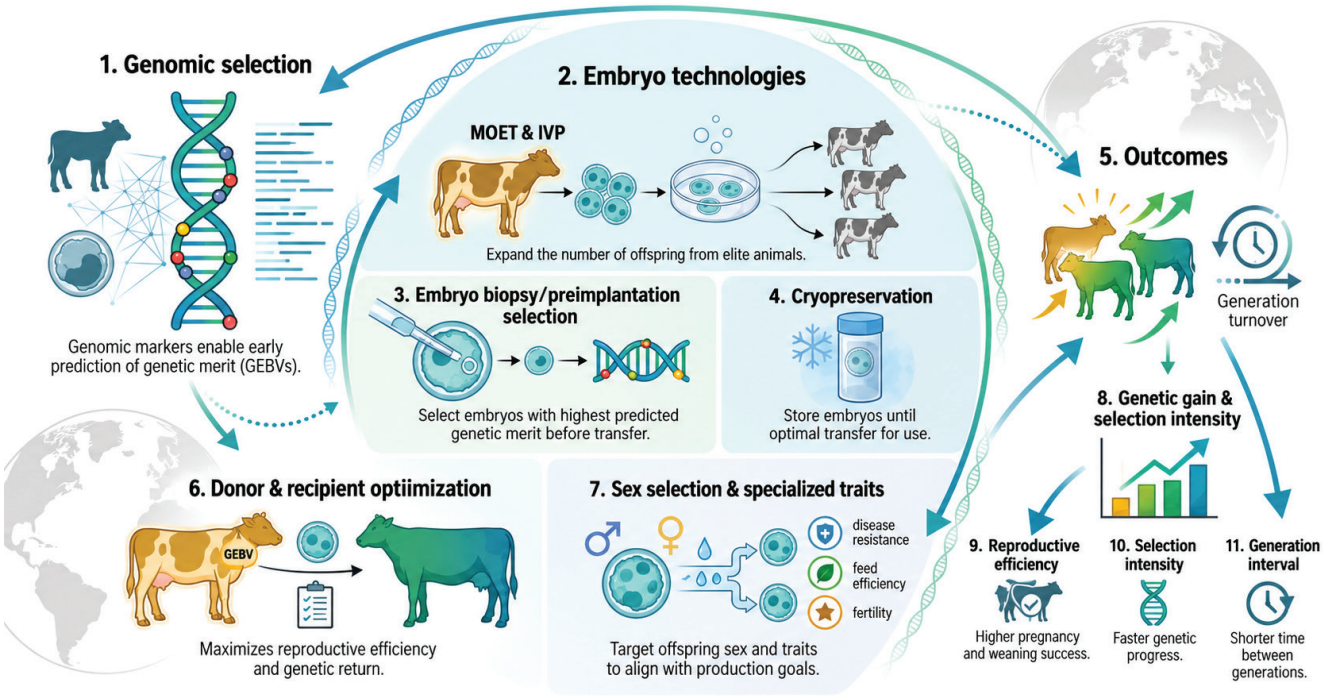


Figure 2. Synergistic integration of genomic selection and embryo technologies in cattle breeding

Consequently, breeding programs must balance technological capability with economic sustainability and operational capacity.[42,63-65]

Technical challenges and costs

Implementation of GS combined with embryo technologies requires specialized infrastructure and technical expertise. Procedures discussed (e.g. OPU, IVP, MOET, embryo biopsy) require advanced equipment and trained personnel.[22,66-68]

OPU involves transvaginal ultrasound-guided aspiration of oocytes and is minimally invasive but technically demanding. Retrieved oocytes must then undergo IVP that includes controlled in vitro maturation, fertilization and embryo culture.[68] Each stage must maintain optimal environmental conditions to preserve embryo developmental competence.

Embryo biopsy enables preimplantation genomic evaluation but introduces additional technical challenges. Removal of a small number of cells must be performed without compromising embryo viability. Techniques (e.g. laser-assisted biopsy, micromanipulation) have improved precision and reduced embryo loss, although these procedures remain labor-intensive and operator-dependent.[31,69]

Cost represents another important limitation. Although genotyping costs have declined markedly, high-density SNP panels used to calculate GEBVs still represent a considerable investment in large-scale programs.[70-73] When combined with expenses associated with OPU sessions, IVP procedures, embryo culture, cryopreservation and transfer, overall costs can be substantial.[68] Therefore, these technologies are most economically justified when applied to elite animals or high-value traits.[74] Strategic selection of donors for genomic screening and embryo production is therefore essential to maximize return on investment.

Pregnancy rates and biological variability

Pregnancy outcomes following embryo transfer remain variable, even under controlled conditions.[75] Multiple biological and management factors influence reproductive success, including donor health, nutritional status and reproductive condition, all of which affect oocyte quality and embryo yield.[75-78]

Recipient selection is equally critical. Recipient cows must have appropriate age, reproductive status and uterine environment to support implantation and pregnancy.[57,75-79] Variations in these factors can influence conception rates, embryo survival and calf viability.

Embryo manipulation, including biopsy for genomic testing, introduces an additional layer of complexity. Although properly performed biopsy procedures generally do not compromise implantation potential, technical factors (e.g. DNA amplification efficiency, genotyping accuracy, handling procedures) may affect outcomes.[80] Errors in genotyping or contamination can lead to discarded embryos or incorrect classification of genetic merit.[81-83] Strict laboratory protocols and quality control measures are therefore essential.

Biological variability also has economic implications. Embryos lost during culture, biopsy, or transfer represent unrecoverable investments in labor, donor productivity, and laboratory resources.[68] To mitigate these risks, breeding programs often produce surplus embryos from elite donors to ensure sufficient numbers of viable offspring.[84-87]

Logistical constraints and genetic diversity

Large-scale implementation of embryo technologies presents logistical challenges. Recipient availability is frequently a limiting factor, particularly in intensive breeding programs where multiple embryos are produced simultaneously.[75] Successful programs require synchronized recipient cycles, adequate facilities, and experienced personnel to manage embryo transfer operations efficiently.[75,86-88]

Intensive use of elite genetics also raises concerns regarding genetic diversity. Programs that concentrate selection on a limited number of high-GEBV donors and sires may accelerate short-term genetic gain but increase the risk of inbreeding.[49] Elevated inbreeding levels are associated with reduced fertility, decreased disease resistance and lower population resilience.[89]

GS provides tools to address these concerns by enabling accurate genomic relationship estimates and facilitating optimized mating strategies. Monitoring population parameters (e.g. effective population size, allele frequency distribution) allows breeders to balance genetic gain with preservation of diversity.[90] Sustainable breeding programs therefore require ongoing genomic monitoring and carefully designed mating strategies to avoid excessive genetic concentration.[91]

Ethical, regulatory and market factors

Adoption of genomic and embryo technologies is also influenced by ethical, regulatory, and market considerations. Regulatory frameworks governing reproductive biotechnologies vary widely among countries, affecting permissible procedures and international embryo trade.[92] Restrictions on embryo manipulation, genetic testing, or cross-border embryo movement may create logistical and compliance challenges for breeders operating internationally.

Consumer perceptions also influence technology adoption. Concerns about genetic manipulation or 'unnatural' breeding practices may affect acceptance, particularly in markets emphasizing organic or natural production systems. Maintaining transparency in breeding practices and adhering to strict animal welfare standards are therefore essential to maintain consumer trust.[93]

Economic viability ultimately depends on alignment with market demand. Traits studied (e.g. fertility, disease resistance, feed efficiency, environmental adaptability) often justify investment in GS and embryo technologies.[94] Breeding programs must therefore align genetic objectives with commercial priorities to ensure sustainable economic returns.

Key message

Integration of GS with advanced embryo technologies has much potential to accelerate genetic improvement in cattle populations. However, successful implementation requires careful management of technical, economic and logistical factors. Procedures (OPU, IVP, embryo biopsy) require specialized infrastructure and expertise whereas biological variability introduces both reproductive and financial risks.

Efficient breeding programs must address logistical constraints, particularly recipient availability and laboratory capacity, while monitoring genomic diversity to avoid excessive inbreeding. Ethical considerations, regulatory frameworks and market acceptance further influence adoption and long-term viability.

A holistic approach that integrates reproductive biotechnology, genomic evaluation, herd management, and economic planning is therefore essential. When carefully implemented, these technologies can substantially accelerate genetic progress while maintaining sustainable and responsible breeding practices.

Limitations and critical challenges

Although the combination of GS and embryo technologies offers substantial opportunities for accelerating genetic gain, several limitations remain. These challenges include genetic, technical, economic, and operational constraints that influence the effectiveness and sustainability of breeding programs. Addressing these factors is essential to ensure responsible and long-term genetic improvement.

Risk of reduced genetic diversity

A major concern associated with intensive genomic selection and embryo technologies is the potential reduction in genetic diversity. Strong selection pressure directed toward a limited number of elite donors and sires can rapidly concentrate favorable alleles while simultaneously narrowing the genetic base of the population.[95] Reduced diversity increases the risk of inbreeding that is associated with decreased fertility, increased disease susceptibility and reduced adaptability to environmental change.

Embryo technologies (e.g. MOET, IVP) can intensify this effect by enabling a single elite female to produce numerous embryos within a short interval.[96] When GS is applied to select embryos with the highest GEBVs, selection intensity increases further, potentially accelerating genetic concentration within breeding populations.

Genomic tools provide strategies to mitigate these risks. Genomic relationship matrices allow breeders to monitor realized relatedness at the DNA level, enabling more accurate management of inbreeding than pedigree information alone. Optimized mate allocation, optimal-contribution selection, monitoring of effective population size, and avoidance of disproportionate contributions from individual elite sires or donor families can help balance short-term genetic gain against preservation of long-term genetic diversity.[97] Genetic gain should therefore not be maximized independently of diversity; rather, genomic breeding programs should establish acceptable rates of inbreeding and routinely monitor genomic relationships, effective population size and changes in allele frequencies across generations.

Biopsy and genotyping constraints

Embryo biopsy and genomic analysis present technical challenges that may influence selection accuracy and embryo viability.[31] Preimplantation genomic selection requires removal of a small number of cells from early-stage embryos for DNA analysis.[29,31,69] Because biopsies yield limited genetic material, genotyping accuracy depends on efficient DNA amplification and robust molecular protocols.

Despite advances in whole-genome amplification and high-density SNP arrays, genotyping errors and incomplete call rates can still occur.[81-83] These limitations may result in misclassification of embryo genetic merit or unnecessary discarding of viable embryos.

Embryo manipulation itself may also influence developmental potential. Although modern biopsy techniques generally preserve embryo viability, improper handling or suboptimal conditions can reduce implantation success.[68,69] Maintaining strict laboratory protocols and experienced technical staff is therefore critical.

Operationally, embryo biopsy and genomic testing also impose logistical constraints. Embryos must be processed rapidly to maintain viability, while genomic analysis must be completed quickly enough to inform transfer decisions.[31] These requirements increase technical complexity and operational costs.

Cost–benefit considerations

Financial considerations represent another limitation in the widespread adoption of genomic embryo selection. Procedures discussed (e.g. OPU, IVP, embryo biopsy, high-density genotyping) involve substantial investment.[70,72] Although genotyping costs have declined substantially, the cumulative expense of integrating multiple advanced technologies can still be considerable.[68]

Economic returns depend heavily on herd structure and breeding objectives. In nucleus breeding programs, even small improvements in genetic merit may generate substantial economic benefits, making genomic embryo selection financially justified.[98] In contrast, commercial herds with average genetic merit may not realize sufficient gains to offset operational costs.

Consequently, many breeding programs adopt a targeted strategy, applying genomic embryo selection primarily to elite donors while using conventional reproductive methods for the broader population.[99] This approach balances genetic progress with economic efficiency.

Operational and logistical limitations

Operational complexity also limits efficiency of GS-assisted embryo technologies. High-throughput embryo production requires coordinated management of donors, recipients, laboratory infrastructure, and trained personnel.[37] Variability in donor ovarian superstimulatory response, recipient fertility and embryo survival can complicate program planning.[68,78,79]

Recipient availability often becomes a bottleneck, particularly when multiple elite donors produce embryos simultaneously. Efficient scheduling, reproductive synchronization and resource allocation are therefore critical components of successful programs.

Failure to manage these operational factors can reduce the realized benefits of genomic technologies, even when genetic merit is accurately identified. Effective program design must therefore integrate reproductive management with genomic selection strategies.

Key message

Integration of GS with embryo technologies offers powerful opportunities for accelerating genetic improvement but also presents important limitations. Intensive selection can reduce genetic diversity whereas technical constraints in embryo biopsy and genotyping may affect accuracy and embryo viability. Financial costs and operational complexity further limit widespread adoption.

Successful breeding programs must therefore balance genetic progress with sustainability, economic feasibility and practical management considerations. Through careful genetic monitoring, rigorous technical standards and strategic use of advanced technologies, breeders can maximize genetic gain while minimizing long-term risks.

Future directions

Integration of GS with advanced embryo technologies has already reshaped cattle breeding, but ongoing technological developments are expected to further enhance efficiency and precision of genetic improvement. Emerging tools, including genome editing, improved genomic prediction models and advanced embryo screening technologies, are likely to integrate with existing reproductive platforms to enable increasingly precise and rapid genetic progress.[53,58] These innovations must, however, be implemented within appropriate ethical, regulatory and economic frameworks to ensure responsible application.[92,93]

Integration with genome editing

Genome editing technologies, particularly CRISPR-Cas9 systems, are a major potential advancement in livestock breeding.[58,100] Unlike conventional selection that relies on naturally occurring genetic variation, genome editing enables targeted modification of specific alleles within an embryo's genome. When combined with GS and embryo technologies (e.g. IVP, MOET, genome editing) could accelerate improvement of traits that are difficult to modify through traditional selection alone.

Potential applications include introduction or enhancement of alleles associated with disease resistance, heat tolerance, feed efficiency and adaptation to changing environmental conditions.[101-103] Welfare-related traits (e.g. polledness or improved calving ease) may also be incorporated into elite embryos identified through GS.[104,105] In this integrated framework, GS identifies embryos with superior overall genetic merit whereas genome editing enables targeted modification of specific loci to achieve precise genetic improvements.

Despite its promise, genome editing raises important ethical, regulatory and societal considerations.[92,93] Many countries maintain strict oversight of genetically modified organisms, and public acceptance of genome-edited livestock remains variable. Concerns regarding animal welfare, unintended off-target mutations and environmental impacts must be carefully addressed before large-scale implementation. Consequently, early applications are likely to occur primarily in research settings or nucleus breeding herds focusing on high-value traits.

Improved prediction models

The effectiveness of GS depends heavily on the accuracy of genomic prediction models and the size and diversity of reference populations.[64,106] Advances in computational biology, data integration and machine learning are expected to improve genomic prediction accuracy.[107] Expanding reference populations across breeds and production systems will enable genomic evaluations to capture a broader range of genetic variation, improving reliability of GEBVs across diverse environments.[108]

Machine learning approaches are particularly promising for analyzing complex datasets and identifying nonlinear relationships among genomic markers and phenotypic traits.[106,109] These methods may improve prediction of polygenic traits (e.g. fertility, feed efficiency, disease resistance) that are influenced by numerous genes and environmental interactions.

Functional genomics may further enhance prediction accuracy by incorporating biological information beyond SNP markers alone. Data on gene expression, regulatory elements and epigenetic modifications may provide additional insight into mechanisms underlying phenotypic variation.[110,111] Integrating functional genomic information with traditional SNP-based evaluations may improve identification of embryos with superior genetic potential and robust performance under diverse environmental conditions.[112,113]

Improved prediction models will be particularly valuable in embryo-based breeding programs, where multiple full and half-sibling embryos can be evaluated simultaneously. Increased GEBV accuracy will enable more confident embryo selection, allowing breeding decisions to be made earlier and with greater precision while reducing reliance on progeny testing.

Enhanced embryo screening

Current embryo selection strategies rely primarily on morphological assessment and genomic testing through biopsy. Emerging noninvasive embryo screening technologies may substantially improve this process by enabling more accurate assessment of embryo viability without compromising developmental potential.[114,115]

Advanced imaging technologies, including time-lapse microscopy and quantitative morphokinetic analysis, allow continuous monitoring of embryo development during culture. These techniques provide detailed information on developmental timing and cellular dynamics that could be used to predict implantation potential and embryo quality.

Artificial intelligence and machine learning algorithms are increasingly being applied to analyze complex imaging and molecular datasets.[116,117] By identifying patterns associated with embryo viability and developmental competence, artificial intelligence-based systems may improve prediction of pregnancy outcomes and long-term performance. Integration of artificial intelligence-assisted imaging with genomic data could enable multi-layered embryo evaluation, combining genetic merit with developmental indicators to optimize embryo selection.[37,56,117]

Additional advances in embryo culture systems, metabolic profiling and automated monitoring may further enhance embryo production efficiency and consistency.[22] Over time, these technologies may reduce the need for invasive biopsy procedures, streamline laboratory workflows and increase the number of high-quality embryos available for transfer.

Integration and future perspectives

The convergence of genome editing, improved genomic prediction models and advanced embryo screening technologies suggests a future in which cattle breeding becomes increasingly data-driven and precision-oriented. GS will continue to provide a foundation for identifying superior genetics, whereas embryo technologies amplify reproductive output and genome editing enables targeted genetic modification. Advanced screening technologies and artificial intelligence-assisted analysis will further optimize embryo selection and reproductive outcomes.

These technologies should be distinguished according to their current level of maturity. Genomic selection, AI, MOET, OPU–IVP, embryo transfer, cryopreservation, and sex-sorted semen are established technologies with commercial application, although adoption varies among production systems. In contrast, AI-assisted embryo ranking, noninvasive molecular or metabolic embryo assessment, embryo-level multi-omics, and many genome-editing applications remain predominantly developmental or research-stage approaches. Broader commercial adoption of these emerging technologies will depend on reproducibility, cost-effectiveness, regulatory approval, animal-welfare considerations and demonstration of improved pregnancy or genetic outcomes under field conditions.

Despite these technological advances, responsible implementation remains essential. Ethical considerations, regulatory frameworks and economic feasibility will ultimately determine the extent to which these technologies are adopted in commercial breeding programs. Although scientific capabilities may enable unprecedented control over genetic outcomes, sustainable herd management and societal acceptance will guide the pace of practical application.

Continued expansion of genomic reference populations, improvements in predictive modeling, and refinements in embryo technologies are likely to drive substantial progress in cattle breeding over the coming decades. When integrated thoughtfully within well-designed breeding programs, these innovations have the potential to accelerate genetic improvement while maintaining animal welfare, genetic diversity and long-term herd sustainability.

Embryo technologies in genomic beef-on-dairy systems

Genomic selection and reproductive technologies have created new opportunities to integrate dairy replacement breeding with the production of higher-value beef-cross calves.[43,58,118] In genomic dairy herds, females can be ranked early according to economic and trait-specific genomic indices, allowing reproductive resources to be allocated according to genetic merit. Elite dairy females may be bred with high-merit dairy sires or enrolled in OPU–IVP programs to generate replacement females whereas lower-ranking dairy females can be bred to genomically selected beef sires.[118-120] This creates a

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tiered breeding structure in which genomic information helps determine which females contribute genetics to the future dairy herd and which are used to produce beef-cross offspring.

OPU–IVP can further increase the contribution of elite dairy females by producing multiple embryos within relatively short intervals.[9,42] Use of sex-sorted dairy semen can preferentially generate female replacements, reducing the number of dairy matings required to maintain herd replacement numbers and consequently increasing the proportion of the remaining herd available for beef-on-dairy matings.[119] Preimplantation genomic testing, as described earlier, may provide an additional level of selection by permitting genomic ranking of embryos before transfer. Embryo-level selection may also capture genetic variation among potential offspring from the same parental combination, complementing approaches that predict gametic variance.[121] Cryopreservation of biopsied embryos can provide additional flexibility in the timing and management of embryo transfer while cryobanking may contribute to preservation of valuable genetic resources.[122,123]

Genomics is equally important on the beef-sire side of the system. Beef sires used on dairy females should be selected for traits appropriate to dairy-beef production, particularly calving ease and pregnancy length, together with birth weight, growth, feed efficiency, carcass merit and other economically relevant terminal traits.[120,124,125] Selection indices specifically developed for beef bulls used on dairy females can facilitate simultaneous consideration of calving performance and the economic value of the resulting crossbred progeny.[120] Selection objectives therefore differ from those used in conventional purebred beef breeding because maternal replacement traits are generally less important when crossbred offspring are intended for terminal beef production.[124,125]

Integration of GS, sex-sorted semen, OPU–IVP, and beef-on-dairy mating allows producers to allocate reproductive resources dynamically according to replacement requirements, genetic merit, reproductive performance, and market conditions.[118,119,124] Economic benefit, however, depends on the cost and efficiency of genomic testing and embryo production, pregnancy success, availability of suitable recipients, and the relative market value of dairy replacements and beef-cross calves.[118] Appropriate sire selection and crossbreeding strategies can further improve the biological and economic value of beef-on-dairy progeny.[120,125] Genomic predictions also require appropriate reference populations because prediction accuracy may decline when genomic models are transferred across breeds or substantially different production environments.[58]

Thus, the principal contribution of embryo technologies to genomic beef-on-dairy systems is not simply the production of more embryos but the strategic allocation of elite dairy genetics and terminal beef genetics within the same herd.[118,124,125] Continued development of crossbred genomic prediction, improved embryo-production efficiency and economic decision tools will determine the extent to which these integrated systems expand.

Global perspectives on genomic selection and assisted reproductive technologies in cattle

Genomic selection and assisted reproductive technologies (ARTs) have transformed cattle breeding worldwide, enabling faster, more accurate and more targeted genetic improvement.[58,126] Traditional breeding relied heavily on phenotypic evaluation and progeny testing that require years of data collection and substantial resources. In contrast, GS utilizes dense genome-wide molecular markers, typically SNPs, to estimate genetic merit early in life.[127,128] By enabling accurate prediction of breeding values at a young age, GS reduces generation intervals, increases selection intensity and accelerates genetic gain.[58,80,128,129]

When combined with ARTs, including AI, MOET, IVP, embryo biopsy and preimplantation genomic testing, GS enables precise propagation of superior genetics.[22] Breeders can select elite parents and evaluate embryos before implantation, allowing embryos with greater predicted genetic merit to be prioritized for transfer. This integration is particularly valuable for traits that are difficult or costly to measure or have low heritability, including fertility, disease resistance and feed efficiency.[129] Adoption of these technologies varies globally depending on breed composition, production systems, infrastructure and policy support.[58,130] The following sections summarize adoption patterns in major milk and meat-producing countries.

United States: large-scale integration of genomic and reproductive technologies

US represents one of the most mature examples of integrating genomic evaluation with reproductive technologies, particularly in dairy cattle. Since the adoption of genomic selection in US dairy breeding programs circa 2009, national genomic evaluations, extensive reference populations, high-density SNP genotyping, and advanced data-management systems have supported increasingly accurate genomic predictions.[128-130] Genomic selection is also firmly established in European and North American dairy breeding programs. In Europe, collaboration among national breeding organizations has enabled the development of large shared Holstein reference populations, increasing the reliability of genomic predictions across participating populations.[131] In North America, US and Canadian dairy populations contributed to the development of genomic prediction systems, illustrating the value of large reference populations and international collaboration for improving prediction reliability.[132]

Assisted reproductive technologies are also established in Canadian dairy breeding. Both in vivo and in vitro embryo-production systems, including OPU–IVP, have been used to increase the reproductive contribution of genetically valuable Holstein donor females.[82] International initiatives (e.g. functional annotation of animal genomes project) further support collaborative genomic research and functional characterization across populations.[133]

An additional consideration is genotype x environment (G x E) interaction. Genomic prediction accuracy depends not only on reference-population size but also on the genetic relationship and environmental similarity between reference and target populations. Genomic models developed in one breed, country, climate, or management system may therefore perform less accurately when applied to genetically distant animals or substantially different production environments. This issue is particularly relevant when genomic tools developed in intensively managed temperate populations are applied to tropical, crossbred, or locally adapted cattle. Expansion of population-specific and multi-breed reference populations,

phenotyping across contrasting environments and incorporation of G x E into genomic evaluation models will be important for improving the robustness of genomic predictions across target populations and production environments.[131,134]

Integration with reproductive technologies further increases the utility of genomic selection. AI and MOET are widely used, while IVP combined with embryo biopsy can enable genomic evaluation of embryos before transfer.[25-31] Embryo-level genomic selection allows embryos with greater predicted genetic merit to be prioritized and reproductive resources to be concentrated on selected candidates.[27,31,33] Modern selection objectives have also expanded beyond production to include fertility, longevity, health, feed efficiency, and environmental sustainability traits.[58,130] In beef cattle, genomic selection combined with ARTs can similarly support improvement in economically relevant traits (growth, carcass performance, reproductive efficiency).[33,58] Overall, the US system illustrates how genomic information and reproductive technologies can be integrated within an increasingly data-driven precision breeding framework.[112]

India: indigenous breed resilience and emerging genomics

India, the world's largest milk producer,[135] presents a unique landscape for GS and ART adoption. The country maintains a vast and genetically diverse cattle population, including indigenous breeds (e.g. Gir, Sahiwal, Tharparkar) alongside crossbred animals with Holstein-Friesian ancestry.[136] Dairy production is dominated by smallholder farms that often operate under low-input systems with limited access to advanced breeding technologies.

Genomic selection remains in an emerging phase. National initiatives (e.g. National Dairy Plan and the Rashtriya Gokul Mission) are developing breed-specific reference populations and genomic evaluation frameworks.[137,138] These programs aim to improve productivity while preserving adaptive traits (e.g. heat tolerance, disease resistance).

AI is widely implemented, particularly in crossbred populations whereas MOET and IVP remain largely confined to research centers and elite breeding herds.[135-140] Integration of GS with ARTs could accelerate propagation of superior genetics in both indigenous and crossbred populations. However, challenges including genotyping costs, limited phenotypic recording and complex population structures constrain large-scale implementation.[141,142]

China: rapid technological adoption

In China, government investment has rapidly expanded adoption of GS and ARTs on large-scale commercial dairy and beef operations.[143,144] Furthermore, ARTs are increasingly integrated with genomic evaluations supported by advanced digital agriculture platforms and high-throughput sequencing technologies.

Selection priorities include milk production, fertility, disease resistance, carcass quality and efficiency within intensive production systems.[144] Preimplantation genomic testing is increasingly explored in elite dairy herds, whereas beef breeding programs use GS to improve growth performance and feed efficiency. Although imported genetics have historically dominated Chinese dairy herds, domestic reference populations are expanding rapidly.[145]

Brazil: genomics and reproductive technologies for tropical production systems

Brazil occupies a prominent position in global cattle breeding, particularly in beef production.[146,147] *Bos indicus* breeds (e.g. Nelore) dominate beef herds whereas Gir and Girolando are widely used in dairy systems adapted to tropical environments.[148]

Brazil also represents a particularly important example of large-scale application of reproductive biotechnology. Brazil has historically been among the global leaders in bovine in vitro embryo production, particularly through extensive use of OPU-IVP in *Bos indicus* cattle (e.g. Nelore).[66,99] The Brazilian experience demonstrates that advanced reproductive biotechnology is not confined to temperate dairy systems and illustrates how OPU-IVP can be deployed at substantial scale in tropical beef-production environments. Genomic selection emphasizes heat tolerance, fertility, longevity and productivity under pasture-based systems.[116] Strong public-private partnerships have supported development of genomic tools tailored to tropical production conditions, illustrating how GS and ARTs can be adapted to nontemperate production systems.[149]

Australia: precision breeding in extensive systems

Australia, a major global beef producer, has integrated GS and reproductive technologies extensively in *Bos taurus* and *Bos indicus* crossbred populations.[33,150] National programs (e.g. BREEDPLAN) provide large reference populations and genomic evaluation frameworks.[151,152]

ARTs are applied primarily in elite herds to accelerate genetic gain for traits including growth rate, carcass quality, fertility, and environmental adaptation. Australia demonstrates how genomic technologies can be applied effectively in extensive production systems.

Pakistan: early development stage

Pakistan's cattle and buffalo populations have critical roles in national milk production but adoption of GS and ARTs remains limited. Dairy systems are dominated by smallholder farms, with buffalo breeds (e.g. Nili-Ravi) and indigenous cattle including Sahiwal and Red Sindhi forming the core production base.[153,154]

Most genomic initiatives are research-based pilot programs conducted through universities and research institutes. AI is relatively common, but MOET, IVP and embryo biopsy remain experimental and confined to research facilities.[155] Major challenges include incomplete animal identification systems, limited phenotypic recording, and constrained financial resources. Nevertheless, targeted investment in genomic infrastructure and reproductive technologies could substantially enhance productivity and genetic improvement.

Global comparative insights

The experiences of major milk/meat-producing countries illustrate the diversity of genomic technology adoption worldwide.[130]

Table. Comparative overview of genomic selection and reproductive technology adoption in major cattle-producing countries

Country	Genomic selection stage	Main focus	Reproductive technology integration
USA	**Established**	Productivity, efficiency, health, fertility and sustainability	AI and MOET widely established; IVP and embryo biopsy used particularly in advanced dairy and elite breeding programs
India	**Developing**	Indigenous breeds, productivity, adaptation and resilience	AI widely used; MOET and IVP more concentrated in organized breeding programs, research centers and elite populations
China	**Rapidly advancing**	Productivity, fertility, efficiency and technological integration	AI, MOET and IVP increasingly integrated with genomic evaluation and digital livestock systems
Brazil	**Established in selected applications**	Tropical adaptation, productivity, fertility and longevity	AI and MOET widely used; OPU–IVP has an established and prominent role, particularly in elite and *Bos indicus* breeding programs
Australia	**Established**	Beef productivity, fertility, carcass traits, and environmental adaptation	AI, MOET, and IVP used primarily in seedstock and elite breeding populations
Pakistan	**Early-development**	Breed characterization, productivity and development of genomic resources	AI more widely accessible; MOET and IVP remain comparatively limited and are concentrated in research or specialized programs

Broad patterns of genomic selection and reproductive technology adoption across selected cattle-producing countries are summarized (Table); adoption may vary among breeds, production sectors and breeding programs within each country is included.

US represents a highly integrated, data-rich breeding system whereas China demonstrates rapid technological expansion supported by large-scale infrastructure.[156] India and Brazil illustrate growing genomic collaboration and the importance of adapting genomic technologies to indigenous and tropical cattle populations.[157] Pakistan illustrates the need for foundational investments in phenotypic recording and breeding infrastructure.[155] Australia demonstrates effective application of genomic and reproductive technologies within extensive beef production systems.[52,150-152] Successful integration of GS and ARTs depends on factors including breed composition, data availability, reproductive management capacity and socio-economic contexts. Where implemented effectively, these technologies accelerate genetic improvement, enhance reproductive efficiency and support sustainable livestock production.

Broadly, GS–ART adoption differs not only among countries but also between production environments. Highly developed cattle-breeding systems generally benefit from large reference populations, extensive phenotyping, established national genetic evaluations, laboratory infrastructure, reliable animal identification and access to specialized reproductive services. In emerging and tropical cattle systems, opportunities may be equally substantial, particularly for improving adaptation, fertility, heat tolerance, disease resilience and production efficiency but implementation may be constrained by smaller or breed-specific reference populations, limited phenotypic recording, genotyping costs, laboratory and cold-chain infrastructure, recipient management, and access to specialized personnel. Importantly, technological development should therefore be adapted to local breed composition, production environment, breeding objectives and economic conditions rather than assuming that models developed in highly intensive temperate populations can be transferred directly to all production systems.

Conclusion

The convergence of genomic selection and advanced reproductive technologies represents a transformative shift in cattle breeding. Technologies (e.g. AI, MOET, IVP, embryo biopsy, embryo cryopreservation) expand reproductive potential whereas genomic tools enable early and accurate identification of superior genetics. Together, these technologies increase selection accuracy, shorten generation intervals, and intensify selection pressure, thereby accelerating genetic improvement for economically important traits. Despite these advantages, successful implementation requires careful management of technical complexity, economic costs and genetic diversity. Challenges related to embryo manipulation, genotyping accuracy, logistical capacity and breeding program design must be addressed to fully realize benefits of integrated genomic and reproductive strategies. Ethical considerations, regulatory frameworks, and market acceptance will also influence adoption trajectories. Looking forward, emerging approaches, including genome editing and noninvasive embryo evaluation, together with continued improvements in established genomic prediction systems, are expected to further enhance the precision and efficiency of livestock breeding. When implemented responsibly, integration of genomic and reproductive technologies offers a powerful framework for sustainable genetic improvement in cattle populations. By combining advanced genomics with reproductive biotechnology, modern breeding programs can improve productivity, resilience and adaptability in both dairy and beef systems, supporting evolving demands of global livestock production.

Conflict of interest

Authors declare no conflicts of interest related to this work.

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References

1. Fleming A, Abdalla EA, Maltecca C, et al: Invited review: reproductive and genomic technologies to optimize breeding strategies for genetic progress in dairy cattle. Arch Anim Breed 2018;61:43-57. doi: 10.5194/aab-61-43-2018
2. Spangler ML, Berry DP, Kuehn LA: Leveraging data from commercial cattle for genetic improvement- an international perspective. J Anim Sci 2025;103:skaf291. doi: 10.1093/jas/skaf291
3. Van Vleck LD: Selection when traits have different genetic and phenotypic variances in different environments. J Dairy Sci 1987;70:337-344. doi: 10.3168/jds.S0022-0302(87)80015-2
4. Mrode R: Best linear unbiased prediction of breeding value: univariate models with one random effect. In: Mrode RA, Thompson R: editors. Models for the Prediction of Animal Breeding Values. Oxfordshire, UK; CABI Publishing: 2014. p. 34-60. doi: 10.1079/9781780643915.0034
5. VanRaden PM, Sullivan PG: International genomic evaluation methods for dairy cattle. Genet Sel Evol 2010;42:7. doi: 10.1186/1297-9686-42-7
6. Goddard ME, Hayes BJ: Mapping genes for complex traits in domestic animals and their use in breeding programmes. Nat Rev Genet 2009;10:381-391. doi: 10.1038/nrg2575
7. Moore SG, Hasler JF. A 100-year review: reproductive technologies in dairy science. J Dairy Sci 2017;100:10314-10331. doi: 10.3168/jds.2017-13138
8. Hansen PJ, Block J: Towards an embryocentric world: the current and potential uses of embryo technologies in dairy production. Reprod Fertil Dev 2004;16:1-14. doi: 10.1071/RD03070
9. Kasinathan P, Wei H, Xiang T, et al: Acceleration of genetic gain in cattle by reduction of generation interval. Sci Rep 2015;5:8674. doi: 10.1038/srep08674
10. Meuwissen THE, Hayes BJ, Goddard ME: Prediction of total genetic value using genome-wide dense marker maps. Genetics 2001;157:1819-1829. doi: 10.1093/genetics/157.4.1819
11. Fujii T: Genomic evaluation and gene expression analysis of preimplantation embryos for enhancing cattle breeding and in vitro embryo production. J Reprod Dev2026;72:590–596. doi: 10.1262/jrd.2026-067
12. Hayes BJ, Bowman PJ, Chamberlain AJ, et al: Genomic selection in dairy cattle: progress and challenges. J Dairy Sci 2009;92:433-443. doi: 10.3168/jds.2008-1508
13. Van Eenennaam AL, Drake DJ: Where in vitro embryo production technology is headed: genetic selection and efficiency improvements. Theriogenology 2012;78:1701-1713. doi: 10.1016/j.theriogenology.2012.07.002
14. Gutierrez-Reinoso MA, Aponte PM, Garcia-Herreros M: Genomic analysis, progress and future perspectives in dairy cattle selection: a review. Animals (Basel) 2021;11:599. doi: 10.3390/ani11030599
15. Rauw WM, Kanis E, Noordhuizen-Stassen EN, et al: Undesirable side effects of selection for high production efficiency in farm animals: a review. Livest Prod Sci 1998;56:15-33. doi: 10.1016/S0301-6226(98)00147-X
16. Hasler JF: Overview of commercial embryo transfer in cattle. Theriogenology 2001;56:1323-1340. doi: 10.1016/S0093-691X(01)00679-5
17. Rizos D, Gutierrez-Adan A, Perez-Garnelo S, et al: Consequences of in vitro culture conditions on embryo development and quality. Theriogenology 2002;57:5-16. doi: 10.1111/j.1439-0531.2008.01230.x
18. Galli C, Duchi R, Crotti G, et al: Bovine embryo technologies. Theriogenology 2003;59:599-616. doi: 10.1016/s0093-691x(02)01243-8
19. Wheeler MB, Rutledge JJ, Fischer-Brown A, et al: Application of sexed semen technology to in vitro embryo production in cattle. Theriogenology 2006;65:219-227. doi: 10.1016/j.theriogenology.2005.09.032
20. Leme LO, Carvalho JO, Mendes CM, et al: Impact of sperm sex sorting on sperm quality and in vitro embryo production in bovine. Anim Reprod Sci 2024;270:107604. doi: 10.1016/j.anireprosci.2024.107604
21. Valente RS, Marsico TV, Sudano MJ: Basic and applied features in the cryopreservation progress of bovine embryos. Anim Reprod Sci 2022;239:106970. doi: 10.1016/j.anireprosci.2022.106970
22. Ferré LB, Kjelland ME, Taiyeb AM, et al: Recent progress in bovine in vitro-derived embryo cryotolerance: Impact of in vitro culture systems, advances in cryopreservation and future considerations. Reprod Domest Anim 2020;55:659-676. doi: 10.1111/rda.13667
23. Kasimanickam R, Kasimanickam V, Kastelic J, et al: Effects of twice daily compared with split-time estrous detection on pregnancy percentage in recipient beef cows. Anim Reprod Sci 2020;219:106526. doi: 10.1016/j.anireprosci.2020.106526
24. Barnes M, Kasimanickam R, Kasimanickam V: Effect of subclinical endometritis and flunixin meglumine administration on pregnancy in embryo recipient beef cows. Theriogenology 2023;201:76-82. doi: 10.1016/j.theriogenology.2023.02.020
25. Mullaart E, Wells D: Embryo biopsies for genomic selection. In: Niemann H, Wrenzycki C: editors. Animal Biotechnology 2. New York, USA; Cham: Springer: 2018. p. 81-94. doi: 10.1007/978-3-319-92348-2_5
26. Silvestri G, Canedo-Ribeiro C, Serrano-Albal M, et al: Preimplantation genetic testing for aneuploidy improves live birth rates with in vitro produced bovine embryos: a blind retrospective study. Cells 2021;10:2284. doi: 10.3390/cells10092284
27. Fujii T, Naito A, Hirayama H, et al: Potential of preimplantation genomic selection for carcass traits in Japanese Black cattle. J Reprod Dev 2019;65:251-258. doi: 10.1262/jrd.2019-009
28. Doultani S, Layek SS, Gohil T, et al: Selecting bovine embryos using genomics tools: sex determination and genetic merit assessment in developing cattle embryos. Reprod Fertil Dev 2023;36:202-203. doi: 10.1071/RDv36n2Ab101
29. Oliveira CS, Silva MVGBD, Quintão CC, et al: Imputation accuracy for genomic selection using embryo biopsy samples in Gir. Reprod Biol 2023;23:100765. doi: 10.1016/j.repbio.2023.100765
30. Shojaei Saadi HA, Vigneault C, Sargolzaei M, et al: Impact of whole-genome amplification on the reliability of pre-transfer

cattle embryo breeding value estimates. BMC Genomics. 2014;15:889. doi: 10.1186/1471-2164-15-889
31. Cenariu M, Pall E, Cernea C, Groza I: Evaluation of bovine embryo biopsy techniques according to their ability to preserve embryo viability. J Biomed Biotechnol 2012;2012:541384. doi: 10.1155/2012/541384
32. VanRaden PM: Efficient methods to compute genomic predictions. J Dairy Sci 2008;91:4414-4423. doi: 10.3168/jds.2007-0980
33. Miller S: Genomic selection in beef cattle creates additional opportunities for embryo technologies to meet industry needs. Reprod Fertil Dev 2022;35:98-105. doi: 10.1071/RD22233
34. Thomasen JR, Willam A, Egger-Danner C, et al: Reproductive technologies combine well with genomic selection in dairy breeding programs. J Dairy Sci 2016;99:1331-1340. doi: 10.3168/jds.2015-9437
35. Sonesson AK, Woolliams JA, Meuwissen TH: Genomic selection requires genomic control of inbreeding. Genet Sel Evol 2012;44:27. doi: 10.1186/1297-9686-44-27
36. Bai Y: Editorial: enhancing livestock breeding through advanced genetic tools and phenotyping systems. Front Genet 2025;16:1617113. doi: 10.3389/fgene.2025.1617113
37. Humblot P, Le Bourhis D, Fritz S, et al: Reproductive technologies and genomic selection in cattle. Vet Med Int 2010;2010:192787. doi: 10.4061/2010/192787
38. Kadarmideen HN, Mazzoni G, Watanabe YF, et al: Genomic selection of in vitro produced and somatic cell nuclear transfer embryos for rapid genetic improvement in cattle production. Anim Reprod Sci 2015;12:8.
39. Loi P, Toschi P, Zacchini F, et al: Synergies between assisted reproduction technologies and functional genomics. Genet Sel Evol 2016;48:53. doi: 10.1186/s12711-016-0231-z
40. Xu Y, Li P, Zou C, et al: Enhancing genetic gain in the era of molecular breeding. J Exp Bot 2017;68:2641-2666. doi: 10.1093/jxb/erx135
41. Lohuis MM: Potential benefits of bovine embryo-manipulation technologies to genetic improvement programs. Theriogenology 1995;43:51-60. doi: 10.1016/0093-691X(94)00016-N
42. Granleese T, Clark SA, Swan AA, et al: Increased genetic gains in sheep, beef and dairy breeding programs from using female reproductive technologies combined with optimal contribution selection and genomic breeding values. Genet Sel Evol 2015;47:70. doi: 10.1186/s12711-015-0151-3
43. Clark SA, Kinghorn BP, Hickey JM, et al: The effect of genomic information on optimal contribution selection in livestock breeding programs. Genet Sel Evol 2013;45:44. doi: 10.1186/1297-9686-45-44
44. Crowe AD, Lonergan P, Butler ST: Invited review: use of assisted reproduction techniques to accelerate genetic gain and increase value of beef production in dairy herds. J Dairy Sci 2021;104:12189-12206. doi: 10.3168/jds.2021-20281
45. Bouquet A, Sørensen AC, Juga J: Genomic selection strategies to optimize the use of multiple ovulation and embryo transfer schemes in dairy cattle breeding programs. Livest Sci 2015;174:18-25. doi: 10.1016/j.livsci.2015.01.014
46. Pryce JE, Hayes BJ, Goddard ME: Novel strategies to minimize progeny inbreeding while maximizing genetic gain using genomic information. J Dairy Sci 2012;95:377-388. doi: 10.3168/jds.2011-4254
47. Seabury CM, Smith JL, Wilson ML, et al: Genome-wide association and genomic prediction for a reproductive index summarizing fertility outcomes in U.S. Holsteins. G3 (Bethesda) 2023;13:jkad043. doi: 10.1093/g3journal/jkad043
48. Melo DB, Bruno RGS, Bisinotto RS, et al: Association of genomic predictions for fertility traits with reproductive outcomes in dairy cows under 2 estrus detection and timed artificial insemination programs. J Dairy Sci 2025;108:2060-2069. doi: 10.3168/jds.2024-25499
49. Norman HD, Hutchison JL, Miller RH: Use of sexed semen and its effect on conception rate, calf sex, dystocia, and stillbirth of Holsteins in the United States. J Dairy Sci 2010;93:3880-3890. doi: 10.3168/jds.2009-2781
50. Goddard ME, Hayes BJ: Genomic selection. J Anim Breed Genet 2007;124:323-330. doi: 10.1111/j.1439-0388.2007.00702.x
51. Chalupková M, Moravčíková N, Halvoník A, et al: Genetic and genomic evaluation of health traits in cattle breeding: a review. Acta Fytotechn Zootechn 2024;27:209-215. doi: 10.15414/afz.2024.27.03.209-215
52. Nguyen TTT, Bowman PJ, Haile-Mariam M, et al: Genomic selection for tolerance to heat stress in Australian dairy cattle. J Dairy Sci 2016;99:2849-2862. doi: 10.3168/jds.2015-9685
53. Berry DP, Crowley JJ: Cell biology symposium: genetics of feed efficiency in dairy and beef cattle. J Anim Sci 2013;91:1594-1613. doi: 10.2527/jas.2012-5862
54. Menchaca A: Assisted reproductive technologies (ART) and genome editing to support a sustainable livestock. Anim Reprod 2023;20:e20230074. doi: 10.1590/1984-3143-AR2023-0074
55. Singh U, Deb R, Alyethodi RR, et al: Genetic features of reproductive traits in bovine and buffalo: lessons from bovine to buffalo. Front Genet 2021;12:617128. doi: 10.3389/fgene.2021.617128
56. Hu G, Do DN, Gray J, et al: Selection for favorable health traits: a potential approach to cope with diseases in farm animals. Animals (Basel) 2020;10:1717. doi: 10.3390/ani10091717
57. Schefers JM, Weigel KA: Genomic selection in dairy cattle: integration of DNA testing into breeding programs. Anim Front 2012;2:4-9. doi: 10.2527/af.2011-0032
58. Demetrio DGB, Benedetti E, Demetrio CGB, et al: How can we improve embryo production and pregnancy outcomes of Holstein embryos produced in vitro? (12 years of practical results at a California dairy farm). Anim Reprod 2020;17:e20200053. doi: 10.1590/1984-3143-AR2020-0053
59. Mueller ML, Van Eenennaam AL: Synergistic power of genomic selection, assisted reproductive technologies, and gene editing to drive genetic improvement of cattle. CABI Agric Biosci 2022;3:13. doi: 10.1186/s43170-022-00080-z
60. Mansour HAEH: Integration of assisted reproductive technologies and artificial intelligence for optimizing fertility and genetic selection in livestock production. Discov Appl Sci 2025;7:1143. doi: 10.1007/s42452-025-07380-9
61. Zhou F, Chen X, Liu S, et al: The clinical application and challenges of preimplantation genetic testing. Front Genet 2025;16:1599088. doi: 10.3389/fgene.2025.1599088

62. McKimmie C, Forutan M, Tajet HM, et al: Impact of implementing female genomic selection and the use of sex-selected semen technology on genetic gain in a dairy herd in New Zealand. Int J Mol. Sci. 2025;26:990. doi: 10.3390/ijms26030990
63. Seno LO, Guidolin DGF, Aspilcueta-Borquis RR, et al: Genomic selection in dairy cattle simulated populations. J Dairy Res 2018;85:125-132. doi: 10.1017/S0022029918000304
64. Zheng X, Wang T, Niu Q, et al: Evaluation of linear programming and optimal contribution selection approaches for long-term selection on beef cattle breeding. Biology (Basel) 2023;12:1157. doi: 10.3390/biology12091157
65. Cornelissen MAMC, Mullaart E, Van der Linde C, et al: Estimating variance components and breeding values for number of oocytes and number of embryos in dairy cattle using a single-step genomic evaluation. J Dairy Sci 2017;100:4698-4705. doi: 10.3168/jds.2016-12075
66. Pontes JH, Nonato-Junior I, Sanches BV, et al: Comparison of embryo yield and pregnancy rate between in vivo and in vitro methods in the same Nelore (Bos indicus) donor cows. Theriogenology 2009;7:690-697. doi: 10.1016/j.theriogenology.2008.09.031
67. Lamb GC, Fontes PLP, Oosthuizen N: In vitro fertilization (IVF) versus multiple ovulation embryo transfer (MOET): Making the decision to use one or both. In: Proceedings, Applied Reproductive Strategies in Beef Cattle; 2019 Aug 20-21; Knoxville, TN. p. 233. Available from: https://beefrepro.org/wp-content/uploads/2020/09/14-Lamb-C.pdf [cited 13 March 2026].
68. Salek F, Guest A, Johnson C, et al: Factors affecting the success of ovum pick-up, in vitro production and cryopreservation of embryos in cattle. Animals (Basel) 2025;15:344. doi: 10.3390/ani15030344
69. Zhang J, Shen H, Zhang Z, et al: Optimisation of laser-assisted biopsy parameters in bovine embryos. Reprod Domest Anim 2026;61:e70184. doi: 10.1111/rda.70184
70. Kelly M, John T: The Economics of Breeding to Improve Eating Quality of Beef using Tenderness Marker Panels. North Sydney, NSW, Australia; The University of Queensland: 2014. Available from: https://www.mla.com.au/research-and-development/reports/2014/the-cost-analysis-of-breeding-to-improve-eating-quality-of-beef-using-genetic-marker-panels [cited 13 March 2026].
71. Khatkar MS, Moser G, Hayes BJ, et al: Strategies and utility of imputed SNP genotypes for genomic analysis in dairy cattle. BMC Genomics 2012;13:538. doi: 10.1186/1471-2164-13-538
72. Tsuruta S, Lourenco DAL, Masuda Y, et al: Reducing computational cost of large-scale genomic evaluation by using indirect genomic prediction. JDS Commun 2021;2:356-360. doi: 10.3168/jdsc.2021-0097
73. VanRaden PM, Cole JB, Parker Gaddis KL: Net Merit as a Measure of Lifetime Profit: 2018 Revision. USDA-AIP Research Report NM$7 (5-18). USA: USDA; 2018. Available from: https://aipl.arsusda.gov/reference/nmcalc-2018.htm [cited 8 September 2019].
74. Boler R, Kasimanickam R: Ovum pick up, in vitro embryo production, and embryo transfer as value-added theriogenology service in miniature Hereford cattle operation. Clinical Theriogenology 2024;16:10528. doi: 10.58292/CT.v16.10528
75. Hansen PJ: The incompletely fulfilled promise of embryo transfer in cattle-why aren't pregnancy rates greater and what can we do about it? J Anim Sci 2020;98:skaa288. doi: 10.1093/jas/skaa288
76. Kasimanickam R, Kasimanickam V: Impact of nutrition on embryo production in cattle: mechanistic insights. Animals (Basel) 2026;16:892. doi: 10.3390/ani16060892
77. Velazquez MA: Nutritional strategies to promote bovine oocyte quality for in vitro embryo production: do they really work? Vet Sci 2023;10:604. doi: 10.3390/vetsci10100604
78. Santos JEP, Cerri RLA, Sartori R: Nutritional management of the donor cow. Theriogenology 2008;69:88-97. doi: 10.1016/j.theriogenology.2007.09.010
79. Bae JW, Jo JH, Uwamahoro C, et al: Biochemical predictors of pregnancy in cattle: enhancing recipient selection for embryo transfer efficiency. Theriogenology 2026;252:117774. doi: 10.1016/j.theriogenology.2025.117774
80. Ponsart C, Salas Cortes L, Jeanguyot N, et al: Le sexage des embryons a le vent en poupe. Bull Tech Insémin Artif 2008;129:30-31.
81. Bouwman AC, Mullaart E: Screening of in vitro-produced cattle embryos to assess incidence and characteristics of unbalanced chromosomal aberrations. JDS Commun 2023;4:101-105. doi: 10.3168/jdsc.2022-0275
82. Jaton C, Schenkel FS, Chud TCS, et al: Genetic and genomic analyses of embryo production in dairy cattle. Reprod Fertil Dev 2019;32:50-55. doi: 10.1071/RD19275
83. Simopoulou M, Sfakianoudis K, Giannelou P, et al: Discarding IVF embryos: reporting on global practices. J Assist Reprod Genet 2019;36:2447-2457. doi: 10.1007/s10815-019-01592-w
84. De Vries A. Economic value of pregnancy in dairy cattle. J Dairy Sci 2006;89:3876-3885. doi: 10.3168/jds.S0022-0302(06)72430-4
85. Sartori R, Balistrieri M, Silva LOE, et al: Pregnancy loss in cattle with emphasis on embryo transfer programs. Anim Reprod 2025;22:e20250045. doi: 10.1590/1984-3143-AR2025-0045
86. Ealy AD, Wooldridge LK, McCoski SR: Post-transfer consequences of in vitro-produced embryos in cattle. J Anim Sci 2019;97:2555-2568. doi: 10.1093/jas/skz116
87. Rizos D, Ward F, Duffy P, et al: Consequences of bovine oocyte maturation, fertilization or early embryo development in vitro versus in vivo: implications for blastocyst yield and blastocyst quality. Mol Reprod Dev 2002;61:234-248. doi: 10.1002/mrd.1153
88. Kathambi EK, Sonstegard TS, Larsen PA: Cross-breeding, advanced reproductive technologies, and genetic selection in twelve dairy production systems in Africa. Animal 2025;19:101424. doi: 10.1016/j.animal.2025.101424
89. Tenghe AMM, Bouwman AC, Berglund B, et al: Genome-wide association study for endocrine fertility traits using single nucleotide polymorphism arrays and sequence variants in dairy cattle. J Dairy Sci 2016;99:5470-5485. doi: 10.3168/jds.2015-10533
90. Tenhunen SR: Balancing genetic gain and diversity in dairy cattle breeding schemes in the genomics era. PhD Dissertation. Aarhus, Denmark; Aarhus University: 2025.
91. Maskal JM, Pedrosa VB, Rojas de Oliveira H, et al: A comprehensive meta-analysis of genetic parameters for resilience and productivity indicator traits in Holstein cattle. J Dairy Sci 2024;107:3062-3079. doi: 10.3168/jds.2023-23668

92. Hallerman E, Bredlau J, Camargo LSA, et al: Enabling regulatory policy globally will promote realization of the potential of animal biotechnology. CABI Agric Biosci 2024;5:25. doi: 10.1186/s43170-024-00225-6
93. Nuffield Council on Bioethics: Genome Editing and Farmed Animal Breeding: Social and Ethical Issues. London, UK; Nuffield Council on Bioethics: 2021. Available from: https://cdn.nuffieldbioethics.org/wp-content/uploads/Genome-editing-and-farmed-animal-breeding-FINAL-WEB-PDF.pdf [cited 13 March 2026].
94. Jones HE, Wilson PB: Progress and opportunities through use of genomics in animal production. Trends Genet 2022;38:1228-1252. doi: 10.1016/j.tig.2022.06.014
95. van Marle-Köster E, Visser C: Unintended consequences of selection for increased production on the health and welfare of livestock. Arch. Anim. Breed 2021;64:177-185. doi: 10.5194/aab-64-177-2021
96. Doublet AC, Restoux G, Fritz S, et al: Intensified use of reproductive technologies and reduced dimensions of breeding schemes put genetic diversity at risk in dairy cattle breeds. Animals 2020;10:1903. doi: 10.3390/ani10101903
97. Bérodier M, Berg P, Meuwissen T, et al: Improved dairy cattle mating plans at herd level using genomic information. Animal 2021;15:100016. doi: 10.1016/j.animal.2020.100016
98. Vries A, Kaniyamattam K: A review of simulation analyses of economics and genetics for the use of in-vitro produced embryos and artificial insemination in dairy herds. Anim Reprod 2020;17:e20200020. doi: 10.1590/1984-3143-AR2020-0020
99. Baruselli PS, de Souza AH, de Sá MF, et al: Genetic market in cattle (Bull, AI, FTAI, MOET and IVP): financial payback based on reproductive efficiency in beef and dairy herds in Brazil. Anim Reprod 2018;15:247-255. doi: 10.21451/1984-3143-AR2018-0091
100. Xu Y, Song L, Wei Z, et al: Application of gene editing technology in cattle genetic breeding. Agric Commun 2025;3:100086. doi: 10.1016/j.agrcom.2025.100086
101. Bishop TF, Van Eenennaam AL: Genome editing approaches to augment livestock breeding programs. J Exp Biol 2020;223 (Suppl_1):jeb207159. doi: 10.1242/jeb.207159
102. Passamonti MM, Somenzi E, Barbato M, et al: The quest for genes involved in adaptation to climate change in ruminant livestock. Animals 2021;11:2833. doi: 10.3390/ani11102833
103. Sonstegard TS, Flórez JM, Garcia JF, et al: Commercial perspectives: genome editing as a breeding tool for health and well-being in dairy cattle. JDS Commun 2024;5:767-771. doi: 10.3168/jdsc.2023-0481
104. Mueller ML, Cole JB, Sonstegard TS, et al: Comparison of gene editing versus conventional breeding to introgress the POLLED allele into the US dairy cattle population. J Dairy Sci 2019;102:4215-4226. doi: 10.3168/jds.2018-15532
105. Aponte PFC, Carneiro PLS, Araujo AC, et al: Investigating the genomic background of calving-related traits in Canadian Jersey cattle. J Dairy Sci 2024;107:11195-11213. doi: 10.3168/jds.2024-24768
106. Wang X, Shi S, Ali Khan MY, et al: Improving the accuracy of genomic prediction in dairy cattle using the biologically annotated neural networks framework. J Anim Sci Biotechno. 2024;15:87. doi: 10.1186/s40104-024-01044-1
107. Hay EH: Machine learning for the genomic prediction of growth traits in a composite beef cattle population. Animals 2024;14:3014. doi: 10.3390/ani14203014
108. Takeda M, Inoue K, Oyama H, et al: Exploring the size of reference population for expected accuracy of genomic prediction using simulated and real data in Japanese Black cattle. BMC Genomics 2021;22:799. doi: 10.1186/s12864-021-08121-z
109. Chafai N, Hayah I, Houaga I, et al: A review of machine learning models applied to genomic prediction in animal breeding. Front Genet 2023;14:1150596. doi: 10.3389/fgene.2023.1150596
110. Xiang R, Breen EJ, Bolormaa S, et al: Integrating extensive functional annotations and multiomics of cattle enhances climate resilience prediction and mapping. Proc Natl Acad Sci USA 2025;122:e2514736122. doi: 10.1073/pnas.2514736122
111. Gao Z, Lu Y, Chong Y, et al: Beef Cattle Genome Project: advances in genome sequencing, assembly, and functional genes discovery. Int J Mol Sci 2024;25:7147. doi: 10.3390/ijms25137147
112. Wang Y, Cui X, Chen Z: Innovations in cattle breeding technology: prospects in the era of gene editing. Animals (Basel) 2025;15:1364. doi: 10.3390/ani1510136
113. Ghoreishifar M, Macleod IM, Chamberlain AJ, et al: An integrative approach to prioritize candidate causal genes for complex traits in cattle. PLoS Genet 2025;21:e1011492. doi: 10.1371/journal.pgen.1011492
114. Rabel RAC, Marchioretto PV, Bangert EA, et al: Pre-implantation bovine embryo evaluation--from optics to omics and beyond. Animals (Basel) 2023;13:2102. doi: 10.3390/ani13132102
115. Magata F: Time-lapse monitoring technologies for the selection of bovine in vitro fertilized embryos with high implantation potential. J Reprod Dev 2023;69:57-64. doi: 10.1262/jrd.2022-131
116. Džermeikaitė K, Šidlauskaitė M, Antanaitis R, et al: Enhancing genomic selection in dairy cattle through artificial intelligence: integrating advanced phenotyping and predictive models to advance health, climate resilience, and sustainability. Dairy (Basel) 2025;6:50. doi: 10.3390/dairy6050050
117. Wells C, Hayden C, Rea M, et al: Advancing bovine embryo evaluation: machine learning to assess embryos in routine embryo transfer practice. J IVF-Worldw 2025;3:45-57. doi: 10.46989/001c.141131
118. Pereira JMV, Ferreira FC, Marcondes MI: Effects of beef semen and beef embryo strategies on profitability: economics of using beef semen and beef in vitro–produced embryo transfer in Jersey herds. J Dairy Sci 2024;107:9491-9503. doi: 10.3168/jds.2023-24530
119. Holden SA, Butler ST: Review: applications and benefits of sexed semen in dairy and beef herds. Anim 2018;12:s97-103. doi: 10.1017/S1751731118000721
120. Berry DP, Amer PR, Evans RD, et al: A breeding index to rank beef bulls for use on dairy females to maximize profit. J Dairy Sci 2019;102:10056-10072. doi: 10.3168/jds.2019-16912
121. Hozé C, Baur A, Fritz S, et al: Prediction of gametic variance and its use in bovine breeding programs. In: Proceedings of the 12th World Congress on Genetics Applied to Livestock Production. Rotterdam; Wageningen Academic Publishers: 2022. p. 1837-1840. doi: 10.3920/978-90-8686-940-4_441

122. González-Rodríguez N, Martínez-Rodero I, Scherzer J, et al: Vitrification and in-straw warming do not affect pregnancy rates of biopsied bovine embryos. Theriogenology 2022;191:221-230. doi: 10.1016/j.theriogenology.2022.07.021
123. Leroy G, Danchin-Burge C, Verrier E, et al: Impact of the use of cryobank samples in a selected cattle breed: a simulation study. Genet Sel Evol 2011;43:36. doi: 10.1186/1297-9686-43-36
124. Mota RR, Brito LF, Berry DP, et al: Editorial: beef on dairy: the use of a simple tool to improve both cattle production systems. Front Genet 2022;13:813949. doi: 10.3389/fgene.2022.813949
125. Basiel BL, Felix TL: Board invited review: crossbreeding beef × dairy cattle for the modern beef production system. Transl Anim Sci 2022;6:txac025. doi: 10.1093/tas/txac025
126. Boichard D, Ducrocq V, Croiseau P, et al: Genomic selection in domestic animals: principles, applications and perspectives. CR Biol 2016;339:274-277. doi: 10.1016/j.crvi.2016.04.007
127. Wiggans GR, Carrillo JA: Genomic selection in United States dairy cattle. Front Genet 2022;13:994466. doi: 10.3389/fgene.2022.994466
128. Schaeffer CH: Strategy for applying genome-wide selection in dairy cattle. J Anim Breed Genet 2006;123:218–223. doi: 10.1111/j.1439-0388.2006.00595.x
129. Mikkola M, Desmet KLJ, Kommisrud E, et al: Recent advancements to increase success in assisted reproductive technologies in cattle. Anim Reprod 2024;21:e20240031. doi: 10.1590/1984-3143-AR2024-0031
130. Van Eenennaam AL: Current and future uses of genetic improvement technologies in livestock breeding programs. Anim Front 2025;15:80-90. doi: 10.1093/af/vfae042
131. Lund MS, de Roos APW, de Vries AG, et al: A common reference population from four European Holstein populations increases reliability of genomic predictions. Genet Sel Evol 2011;43:43. doi: 10.1186/1297-9686-43-43
132. VanRaden PM, Van Tassell CP, Wiggans GR, et al: Invited review: reliability of genomic predictions for North American Holstein bulls. J Dairy Sci 2009;92:16-24. doi: 10.3168/jds.2008-1514
133. Andersson L, Archibald A, Bottema C, et al: Coordinated international action to accelerate genome-to-phenome with FAANG, the Functional Annotation of Animal Genomes project. Genome Biol 2015;16:57. doi: 10.1186/s13059-015-0622-4
134. Pryce JE, Gredler B, Bolormaa S, et al: Short communication: genomic selection using a multi-breed, across-country reference population. J Dairy Sci 2011;94:2625-2630. doi: 10.3168/jds.2010-3719
135. Prabhakar P, Bharti SK, Kumar P, et al: Challenges and strategies for sustainable dairy farming in India: a review. Int J Curr Microbiol Appl Sci 2020;(Special Issue 11):4065-4071.
136. Sahana VN, Gowane GR, Nayee N, et al: Shared SNP effects across breeds increase the genomic prediction accuracy for numerically small breeds. Sci Rep 2025;15:31421. doi: 10.1038/s41598-025-15733-y
137. Ministry of Fisheries, Animal Husbandry & Dairying. Azadi Ka Amrit Mahotsav: Rashtriya Gokul Mission: 2023. Available from: https://www.pib.gov.in/PressReleasePage.aspx?PRID=2099675 [cited 12 March 2026].
138. Ministry of Fisheries, Animal Husbandry & Dairying. Azadi Ka Amrit Mahotsav: New Technologies in Animal Husbandry and Dairy. 2023. Available from: https://www.pib.gov.in/PressReleseDetailm.aspx?PRID=2149835 [cited 12 March 2026].
139. Admin. Genomic Selection in Indian Cattle and Buffalo: A Game-Changer for Smallholder Dairy Farmers. 2025. Available from: https://baif.org.in/genomic-selection [cited 12 March 2026].
140. Saravanan KA, Panigrahi M, Kumar H, et al: Progress and future perspectives of livestock genomics in India: a mini review. Anim Biotechnol 2023;34:1979-1987. doi: 10.1080/10495398.2022.2056046
141. Burrow HM, Mrode R, Mwai AO, et al: Challenges and opportunities in applying genomic selection to ruminants owned by smallholder farmers. Agriculture 2021;11:1172. doi: 10.3390/agriculture11111172
142. Li X, Wang S, Huang J, et al: Improving the accuracy of genomic prediction in Chinese Holstein cattle by using one-step blending. Genet Sel Evol 2014;46:66. doi: 10.1186/s12711-014-0066-4
143. Wang W, Li L, Chen Y, et al: Whole-genome resequencing and genetic diversity of five indigenous cattle breeds from China. Sci Data 2026;13:282. doi: 10.1038/s41597-026-06610-y
144. Liu D, Xu Z, Zhao W, et al: Genetic parameters and genome-wide association for milk production traits and somatic cell score in different lactation stages of Shanghai Holstein population. Front Genet 2022;13:940650. doi: 10.3389/fgene.2022.940650
145. Liu Y, Liu S, Sheng H, et al: Revolutionizing cattle breeding: gene editing advancements for enhancing economic traits. Gene 2024;927:148595. doi: 10.1016/j.gene.2024.148595
146. Madalena FE, Peixoto MGCD, Gibson J: Dairy cattle genetics and its applications in Brazil. Livest Res Rural Dev 2012;24:97.
147. McManus C, Albuquerque LG, Dias LT, et al: Livestock breeding, conservation and genomics in Brazil: who, when, where, and what. Livest Sci 2024;281:105429. doi: 10.1016/j.livsci.2024.105429
148. Marchioretto PV, Rabel RAC, Allen CA, et al: Development of genetically improved tropical-adapted dairy cattle. Anim Front 2023;13:7-15. doi: 10.1093/af/vfad050
149. Santos JB, Salvarani FM: Impacts of climate change on cattle health and production in the Brazilian Amazon biome. Ruminants 2025;5:58. doi: 10.3390/ruminants5040058
150. Johnston DJ, Tier B, Graser HU: Beef cattle breeding in Australia with genomics: opportunities and needs. Anim Prod Sci 2012;52:100-106. doi: 10.1071/AN11116
151. Scott BA, Haile-Mariam M, Cocks BG, et al: How genomic selection has increased rates of genetic gain and inbreeding in the Australian national herd, genomic information nucleus, and bulls. J Dairy Sci 2021;104:11832-11849. doi: 10.3168/jds.2021-20326
152. Burnham R: Optimising Beef Genetic Selection in Northern Australia. Nuffield Scholar Report. 2019. Available from: https://www.nuffieldscholar.org/sites/default/files/2021-02/Rebecca%20Burnham%20Nuffield%20Report_FINAL%20reviewed2_0.pdf [cited 13 May 2026].
153. Muner RD, Moaeen-Ud-Din M, Saleem AH, et al: Genomic selection, gene editing, and reproductive biotechnology: a triad for the improvement of native buffalo breeds in a developing

country perspective like Pakistan. Trop Anim Health Prod 2025;57:102. doi: 10.1007/s11250-025-04352-4

154. Islam S, Reddy UK, Natarajan P, et al: Population demographic history and population structure for Pakistani Nili-Ravi breeding bulls based on SNP genotyping to identify genomic regions associated with male effects for milk yield and body weight. PLoS One 2020;15:e0242500. doi: 10.1371/journal.pone.0242500
155. National Food Security and Research, Ministry of National Food Security, Pakistan. Pakistan Launches Historic Public-Private Genomics Venture to Revolutionize Food Security and Biotechnology. 2025. Available from: https://www.nfsr.gov.pk [cited 12 March 2026].
156. Bai Z, Ma W, Ma L, et al: China's livestock transition: driving forces, impacts, and consequences. Sci Adv 2018;4:eaar8534. doi: 10.1126/sciadv.aar8534
157. ANI. India, Brazil seal landmark animal genomics partnership to transform global dairy future: a strategic South-South alliance for global food security. ANI News: 2025. Available from: https://www.aninews.in [cited 12 March 2026].