Explor Anim Med Res.
Vol. 15, Issue 1, 2025
DOI: 10.52635/eamr/15.1.4-15

ISSN 2277-470X (Print), ISSN 2319-247X (Online)
Website: www.animalmedicalresearch.org

Review Article

ADVANCING BOVINE FETAL SEXING IN INDIA: STRATEGIC TECHNOLOGICAL AND POLICY PERSPECTIVES - A REVIEW

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Received 18 December 2024, revised 27 April 2025

ABSTRACT: Bovine fetal sexing technology is emerging as a key innovation in the Indian dairy and livestock industries, enabling early determination of calf sex during gestation. This technology supports strategic herd composition by favoring the production of female calves for milk yield and male calves for beef, enhancing productivity and economic returns. Techniques such as ultrasound, DNA-based methods (e.g., PCR and cell-free fetal DNA analysis), and fluorescence in situ hybridization (FISH) offer various fetal sexing options. Each method has unique advantages in terms of accuracy, cost, and invasiveness. Recent advances such as AI-assisted imaging and liquid biopsy have further improved accessibility, especially in rural areas. Bovine fetal sexing also contributes to genetic improvement and animal welfare by reducing the birth of economically less viable male calves. Despite its benefits, challenges including high costs, lack of infrastructure, and limited rural access restrict its widespread use. This review outlines the development and application of fetal sexing technologies, their economic and ethical implications, and the strategic relevance of these tools in the Indian context. It also provides policy recommendations, highlights the role of public-private partnerships, and suggests pathways to improve access through research, innovation, and skill development.

Keywords: Bovine fetal sexing, Dairy farming, Derd optimization, Genetic improvement, Reproductive technologies.

INTRODUCTION

The Role of Dairy and Livestock in the India's Economy

India has consistently held the position of the world's largest milk producer, contributing approximately 22% of the global supply. The livestock sector, especially dairy farming, is vital to the rural economy, supporting millions of small and marginal farmers. According to the National Dairy Development Board (NDDB), about 70 million rural households depend on dairy for their livelihoods. The dairy industry is a major driver of agricultural growth, contributing roughly 4.2% to India's GDP and enhancing food security, nutrition, and income in rural areas [57]. Beyond dairy, livestock supports meat, leather, and wool industries, with cattle, buffaloes, goats, and sheep being key resources for agriculture and commerce. In the last decade, efforts to boost dairy sector productivity have focused on technological advancements in breeding, health management, and nutrition.[82]. Cattle play a pivotal role in the rural economy, serving as both milk producers and draught animals. The rising demand for high-quality milk-producing cattle has intensified selective breeding and genetic improvement initiatives, driving the adoption of advanced livestock management practices. In the last decade, efforts to boost dairy sector productivity have focused on technological advancements in breeding, health management, and nutrition. As these advancements evolve, emerging biotechnological and reproductive innovations, such as bovine fetal sexing, are gaining attention for their potential to revolutionize dairy farming practices, particularly in a system where female calves are highly sought after for their higher milk yield, lower input costs, and cultural significance [40].

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Enhancing dairy productivity: bovine fetal sexing vs. sexed semen in herd management

Bovine fetal sexing, a technique that allows for the determination of the sex of a fetus before birth, has emerged as a valuable tool in livestock management. The process can be performed using several advanced technologies, including ultrasound, polymerase chain reaction (PCR)-based methods, and emerging non-invasive techniques such as blood-based assays and DNA analysis from milk samples. These methods are gaining traction due to their ability to determine fetal sex without the need for invasive procedures. Alongside fetal sexing, sexed semen serves as a parallel technology, offering another option for selectively breeding female calves to optimize herd composition and improve dairy productivity. This technology holds significant relevance for the dairy and livestock industry in India, where the gender of calves plays a crucial role in herd optimization. In traditional farming systems, male calves are often less economically valuable to dairy farmers compared to female calves, who contribute directly to milk production [67]. Therefore, the ability to predict and selectively breed female calves offers substantial economic advantages to dairy farmers.

The process of bovine fetal sexing can be performed using several advanced technologies, including ultrasound, polymerase chain reaction (PCR)-based methods, and emerging non-invasive techniques. By utilizing these technologies, farmers can make informed decisions about breeding strategies, resource allocation, and herd management. For example, ultrasound can determine the sex of a fetus as early as 55-60 days of gestation, allowing farmers to adjust their breeding programs to favor the birth of female calves. However, while these tools are precise, their availability at the farm level in rural India may be limited, often requiring access to institutional setups or veterinary professionals equipped with specialized technology [84]. This may present challenges in terms of accessibility for smaller-scale farmers, making the implementation of such technologies more feasible in larger operations or with the assistance of veterinary service providers.

Beyond the direct economic benefits, fetal sexing also aligns with broader animal welfare and ethical considerations. By enabling farmers to reduce the number of unwanted male calves, this technology helps address issues related to the neglect or improper care of male calves, which often face a lack of economic utility in dairy farming. Furthermore, by enhancing herd composition, bovine fetal sexing contributes to better long-term health outcomes for livestock, as farmers can manage their herds more efficiently, with a focus on productive and healthy animals [39].

The relevance of bovine fetal sexing becomes even more pronounced in the context of India's growing population and the rising demand for dairy products. As the dairy industry continues to expand, there is an increasing need for sustainable practices that can meet this demand while ensuring animal welfare and farm profitability. Bovine fetal sexing presents a valuable solution, with the potential to optimize livestock management, reduce waste, and improve the economic viability of dairy farms across the country. However, in rural India, accessibility to these technologies may be limited due to barriers such as high costs, lack of trained professionals, and inadequate infrastructure, making widespread adoption a challenge for small-scale farmers [3]. This review examines bovine fetal sexing technology's role in advancing India's dairy and livestock sectors. It covers historical and current techniques, economic and genetic benefits, and challenges such as costs, awareness, and rural access. Highlighting the potential for widespread adoption, the review discusses how policies, private initiatives, and innovation can drive sustainable growth in India's dairy industry [76]. It aims to guide farmers, policymakers, and researchers on using fetal sexing to boost productivity, animal welfare, and rural development while encouraging further advancements [79].

HISTORICAL DEVELOPMENT OF BOVINE FETAL SEXING TECHNIQUES

Early methods of sex determination in livestock

The need to determine the sex of livestock has been long-standing, particularly in dairy farming where female calves are preferred for milk production. In earlier times, farmers relied primarily on observational methods, including folklore, to predict the sex of offspring. These traditional methods often included observing the behavior of the animal during pregnancy or noting specific physical traits, such as the positioning of the fetus or the shape of the cow's abdomen. For example, in some rural Indian practices, it was believed that if the fetus was positioned on the right side of the dam, it would be male, while the left side indicated a female calf. However, these practices were largely anecdotal, with little to no scientific validation, leading to unreliable outcomes [87]. However, these practices were largely anecdotal, with little to no scientific validation, leading to unreliable outcomes.

Another early approach was based on selective breeding practices. Farmers would pair specific male and female animals, often based on the assumption that certain bulls produced more female offspring. This approach, while slightly more systematic, still lacked precision and depended on chance rather than concrete biological indicators [47]. The desire to improve these outcomes sparked interest in more scientific approaches to fetal sex determination as agriculture and animal husbandry practices became more commercialized. The first serious attempts to scientifically determine the sex of unborn livestock can be traced back to the mid-20th century. Researchers began exploring chromosomal sex determination and the biology of early embryonic development to find reliable markers of sex differentiation [31]. This marked the beginning of an era where scientific inquiry sought to replace traditional practices with verifiable techniques.

Evolution of Sexing Technologies Over the Years

While traditional methods of sex determination remained largely speculative and unscientific, the growing need for more accurate and reliable techniques led to significant advancements in reproductive biology. The evolution of sexing technologies gained momentum in the latter half of the 20th century with significant advances in reproductive biology. One of the first breakthroughs came with the discovery of the XY chromosome system in mammals, which clearly differentiated male and female offspring based on the presence of specific sex chromosomes. This led to the development of techniques like karyotyping, which allowed researchers to identify the chromosomal composition of cells under a microscope. Karyotyping became a foundational tool for accurate sex determination, particularly in the early stages of genetic research. It was used in laboratory settings to examine the chromosomes of embryos, enabling precise identification of male and female offspring based on the presence of the XY or XX chromosome pair. While highly accurate, karyotyping was time-consuming and required invasive methods, limiting its practical application in field settings [96].

In the 1970s, researchers began to apply more sophisticated methods involving the collection and analysis of embryonic cells. Embryo biopsy techniques were developed, where a small sample of cells was taken from an embryo to determine its sex based on the presence of Y-chromosome specific markers. This technique represented a significant leap forward, as it was able to provide accurate sexing results early in the gestation process [54]. However, the invasive nature of this method raised concerns about the viability of the embryo and its development post-biopsy.

The 1980s and 1990s saw the introduction of ultrasound technology as a non-invasive method for fetal sexing. Ultrasound was initially used to observe the general development of the fetus but soon became a key tool in determining fetal sex by visualizing the genital tubercle, which differentiates into male or female reproductive organs [91]. By the late 1990s, advancements in ultrasound imaging, such as high-resolution and 3D ultrasounds, significantly improved the accuracy of sexing techniques. Farmers were now able to reliably determine the sex of the fetus within the first trimester of pregnancy without harming the animal.

In parallel, molecular biology techniques such as polymerase chain reaction (PCR) gained prominence in sex determination. PCR allowed for the amplification of specific DNA sequences, enabling scientists to detect the presence of the Y chromosome in fetal DNA obtained from the mother's blood or through amniotic fluid sampling [60]. This molecular approach represented a major improvement in accuracy and reduced the need for invasive procedures.

The turn of the millennium introduced another major advancement with the development of preimplantation genetic diagnosis (PGD), a technique that evolved from embryo biopsy methods used in reproductive research. In PGD, a few cells are carefully extracted from early-stage embryos—typically created via in vitro fertilization (IVF)—to test for genetic markers, including sex chromosomes, before the embryo is implanted. While PGD originated in human medicine to screen for genetic disorders, it has found increasing application in elite livestock breeding programs where precise control over the sex of offspring is economically beneficial [97]. PGD offers nearly 100% accuracy in determining the sex of embryos, allowing for the selective implantation of female embryos to boost dairy productivity or male embryos in beef production. However, the use of PGD in animal breeding raises ethical considerations related to the manipulation of embryos, the welfare of surrogate animals, and the broader implications of genetically selecting livestock for commercial traits.

Milestones in the Development of Modern Techniques

One of the most significant was the introduction of non-invasive prenatal testing (NIPT), which uses cell-free fetal DNA (cffDNA) circulating in the maternal bloodstream to determine the sex of the fetus [38]. cffDNA originates from the placenta and mirrors the fetal genome, making it a reliable and accurate source for early prenatal testing. NIPT represents a substantial leap forward as it eliminates the need for invasive procedures and provides early, accurate results. By extracting fetal DNA from the mother's blood, researchers can test for the presence of male-specific Y-chromosome markers as early as seven weeks into gestation [1]. This technique is particularly advantageous in dairy farming, where early sex determination can significantly impact breeding decisions and resource allocation.

Another milestone in modern fetal sexing is the integration of artificial intelligence (AI) and machine learning into ultrasound and molecular testing. AI algorithms—particularly convolutional neural networks (CNNs)—have been successfully applied to fetal imaging in livestock, demonstrating high accuracy in classifying fetal sex based on key ultrasound features [87]. These systems reduce human error and enable real-time decision-making during veterinary visits, making sexing more accessible to smaller farms and operations with limited technological resources.

Modern PCR techniques have evolved to include real-time quantitative PCR (qPCR), which enables the precise quantification of Y-chromosome DNA in maternal blood samples. The key diagnostic threshold in qPCR is the cycle threshold (Ct) value, where a lower Ct value indicates a higher concentration of target DNA, such as Y-chromosome markers, and confirms male fetal sex. This advancement significantly enhances the accuracy and reliability of fetal sex determination. As the cost of qPCR technology decreases, it becomes increasingly accessible to a wider range of veterinary practices and farm operations. Its non-invasive nature and ability to provide early results in pregnancy make it a practical and efficient tool for farmers to make informed breeding and management decisions [68].

The rise of genomic technologies has further revolutionized the field. Techniques such as next-generation sequencing (NGS) provide a more detailed analysis of fetal DNA, allowing not only for sex determination but also for the identification of genetic traits and predispositions [58]. This development has significant implications for livestock breeding, where the ability to select for specific traits alongside sex can lead to more productive and resilient herds.

In addition to these technological advancements, policy support and research funding have played critical roles in the adoption of bovine fetal sexing. Governments and agricultural organizations have increasingly recognized the economic and ethical benefits of fetal sexing, leading to initiatives that promote the use of these technologies in rural and semi-urban farming communities [71]. The widespread adoption of these techniques has been further facilitated by the growing availability of mobile ultrasound units and on-site DNA testing kits, which allow farmers to perform sexing tests directly on their farms.

CURRENT BOVINE FETAL SEXING TECHNOLOGIES

Ultrasound-based methods

Ultrasound-based fetal sexing is a non-invasive, cost-effective, and early-detection method that aids in efficient breeding and resource allocation. While the method is non-invasive and cost-effective, its reliability hinges on operator expertise and conducting the scan within the optimal gestational window.

The ideal time for ultrasound-based sex determination is between 55 and 70 days of gestation, when the genital tubercle—an early structure that later develops into the penis or clitoris—is clearly visible. In female fetuses, the tubercle is located near the tail, whereas in males, it is near the umbilical cord [45]. Advances in ultrasound technology, including 3D and 4D imaging, have further improved the precision of this method. Reported accuracy rates range from 80% to 95%, depending on operator expertise and timing [91].

DNA-based sex determination

DNA-based sex determination is one of the most accurate methods available today for fetal sexing in bovines. The two main techniques used are polymerase chain reaction (PCR) and non-invasive fetal DNA analysis (Table-1). Both methods detect the presence of Y-chromosome-specific markers to determine the sex of the fetus [4].

Polymerase chain reaction (PCR)

This method involves the extraction of fetal DNA from maternal peripheral blood (non-invasive) or amniotic fluid (invasive), followed by amplification of sex-linked markers. PCR techniques allow for the detection of the Y chromosome, indicating a male fetus [62]. PCR-based methods have an accuracy rate of 98–99% and can be performed as early as 50 days post-conception. While maternal blood sampling is considered minimally invasive, amniocentesis provides a more direct sample but involves a higher degree of invasiveness [13].

Non-invasive fetal DNA analysis

Recently, the development of cell-free fetal DNA (cffDNA) testing has provided a non-invasive option

Table 1. Timeline for fetal sex determination using DNA-based methods

Methods	Timing for Accuracy	Sample Type	Accuracy	Cost	References
PCR	50-60 days	Maternal blood or amniotic fluid	98-99%	High	[35]
Non-invasive cff DNA	40-45 days	Maternal blood	0.99	High	[88]

for sex determination. This method analyzes fetal DNA circulating in the mother's bloodstream to determine the presence of male-specific DNA sequences. cffDNA testing has proven to be highly accurate and can be performed even earlier than traditional methods, offering results as early as 40-45 days into gestation [96].

While PCR and non-invasive fetal DNA analysis are highly accurate, they require specialized laboratory equipment, making them less accessible to small-scale farmers. These techniques are also more expensive than ultrasound-based methods, which limits their widespread adoption in developing countries [5].

Fluorescence *in situ* hybridization (FISH)

Fluorescence *in situ* hybridization (FISH) is an advanced technique used for sex determination by detecting the presence of specific DNA sequences in fetal cells. This method involves applying fluorescent probes that bind to sequences unique to the X or Y chromosomes. The binding of these probes allows for the visual differentiation of male and female fetuses under a microscope [88].

FISH is highly accurate, with a success rate of approximately 99%. It is typically used in high-value breeding programs where precision is paramount. The technique is applied primarily in embryos that have been biopsied during in vitro fertilization (IVF) procedures or through amniocentesis. While FISH is highly effective, its invasiveness limits its use in standard farming practices, particularly for small-scale operations.

One of the major advantages of FISH is its ability to analyze multiple genetic markers simultaneously, enabling both sex determination and the screening for inherited diseases or economically important traits [58]. This dual utility makes FISH a valuable tool in the genetic management of livestock, especially in high-performance breeding operations that aim to optimize herd quality.

Despite its high accuracy, the cost and technical expertise required for FISH make it less practical for widespread use in everyday farming. Additionally, its invasive nature poses risks to the fetus, making it a less favorable option for farmers concerned about animal welfare.

The comparison of fetal sexing methods in the (Table-2) above highlights the differences in accuracy, timing, invasiveness, and cost efficiency across three techniques: ultrasound, PCR, and FISH.

Innovations in fetal sexing technologies

In recent years, significant progress has been made in developing novel and less invasive technologies for bovine fetal sex determination. These emerging techniques promise to improve accessibility, affordability, and accuracy in livestock management [4].

Liquid biopsy

This method is one of the most exciting developments in fetal sexing technology. Liquid biopsy refers to the sampling and analysis of non-solid biological tissues, primarily blood. In the context of fetal sexing, it involves extracting fetal DNA from the maternal bloodstream to detect Y-chromosome markers. The non-invasive nature of this procedure, coupled with its early detection capabilities, makes it a valuable tool in herd management. Liquid biopsy is currently being refined for broader agricultural applications, but initial results show great promise in terms of accuracy and efficiency [55].

AI integration in ultrasound

Artificial intelligence (AI) is increasingly being integrated into ultrasound technologies to enhance accuracy and reduce the reliance on technician expertise. AI algorithms can analyze ultrasound images in real time, automatically identifying key markers for fetal sexing. These AI-driven tools have been shown to improve the accuracy of sex determination, particularly when used in conjunction with high-resolution ultrasound equipment [97].

CRISPR and gene editing

Although still in the experimental phase, gene-editing technologies such as CRISPR are being explored for their potential in livestock management. CRISPR could theoretically allow for the selection

Table 2. Comparison of accuracy in fetal sexing methods

Methods	Accuracy	Timing (Days Post-Conception)	Invasiveness	Cost Efficiency	References
Ultrasound	90-95%	55-70 days	Non-invasive	Moderate	[85]
PCR	98-99%	50-60 days	Minimally invasive	High	[34]
FISH	0.99	40-50 days	Invasive	High	[45]

or even modification of specific traits, including sex, in embryos. While these technologies are not yet commercially viable for routine sexing, they represent the cutting edge of genetic management in livestock breeding [71]. While still in the conceptual or research phase, such tools hint at a future where selective embryo production may be possible based on predefined sex and genetic characteristics, potentially reshaping herd demographics and productivity planning.

Each of these emerging technologies offers unique advantages and has the potential to revolutionize bovine fetal sex determination in the coming years. However, they also present challenges, particularly in terms of cost, accessibility, and ethical considerations. The integration of these technologies into standard farming practices will depend on continued advancements in research, policy support, and cost reduction strategies.

ECONOMIC AND GENETIC IMPLICATIONS

Economic benefits

The dairy industry in India, which plays a vital role in the rural economy, is primarily dependent on milk production, and the birth of female calves is central to maintaining productive herds. Bovine fetal sexing technology offers an opportunity to optimize herd composition by enabling farmers to increase the number of female calves. This not only enhances milk production but also reduces the cost associated with maintaining unproductive male calves [83].

Given that female calves mature into milk-producing cows, fetal sexing allows for more predictable planning in dairy farm operations. It provides an effective method for improving herd productivity over time, as farmers can selectively increase the proportion of female offspring, which directly correlates to higher milk yields. Studies have shown that farms employing fetal sexing can experience a 20-25% increase in milk production over a five-year period due to a more balanced and efficient herd composition [62]. From an economic perspective, the application of fetal sexing technology leads to significant cost savings for farmers. Traditionally, the birth of male calves often results in financial strain since these animals are of limited use in dairy operations. With sexing technology, farmers can minimize these inefficiencies by predominantly producing female calves, which are essential for sustaining and expanding milk production. The reduction in the number of male calves also lowers the associated costs of feed, veterinary care, and other inputs needed to raise unproductive livestock [85]. The long-term financial gains for farmers are substantial, as fetal sexing not only enhances milk production but also increases the genetic quality of herds. By ensuring a steady supply of high-value female calves, farmers can optimize resource allocation, reduce wastage, and ultimately enhance the profitability of their operations [26]. Furthermore, by improving herd efficiency, farmers can better withstand market fluctuations and economic pressures, making dairy farming more sustainable in the long run.

Selective breeding for herd improvement

The ability to control the sex of calves through fetal sexing represents a major advancement in selective breeding programs. Selective breeding has long been a cornerstone of herd improvement, but the introduction of fetal sexing technology allows farmers to take this practice a step further by strategically influencing the gender ratio of their herds. This is especially important in the context of India's dairy industry, where the focus is on maximizing milk production [73]. Fetal sexing enables farmers to selectively breed for female offspring, allowing for more efficient use of high-quality genetics. Farmers can focus on breeding cows with superior milk production traits, leading to the creation of herds with enhanced genetic characteristics over time. This results in increased productivity and greater resilience to diseases, as better-bred cows tend to have stronger immune systems and better overall health [43].

Impact on gender ratio and dairy output

One of the most significant impacts of fetal sexing technology is the ability to manipulate the gender ratio of livestock herds. In traditional breeding practices, the birth of male and female calves occurs at roughly equal rates. However, with the use of sexing technologies, farmers can significantly skew this ratio in favor of female calves, which are more economically valuable in dairy operations [56].

The resulting improvement in gender ratios directly influences dairy output, as a larger proportion of female calves leads to a more productive herd. Research has indicated that farms using fetal sexing experience a marked increase in dairy yields, with studies reporting as much as a 30% improvement in milk production over a 10-year period [15]. By consistently producing more female calves, farmers can plan for long-term growth in milk production and stabilize their operations.

Reducing the number of unproductive male calves

The traditional breeding cycle often results in a large number of male calves, which have limited utility in the dairy industry. These calves are often considered a financial burden and, in some cases, may suffer from neglect due to their lack of economic value. The introduction of fetal sexing technology addresses this issue by significantly reducing the number of male calves born on farms [10].

By minimizing the birth of unproductive male calves, farmers can allocate resources more efficiently and focus on the health and well-being of their herds. This reduction in the number of male calves also helps mitigate issues related to overpopulation and the associated environmental impacts, such as the need for additional land and feed. Furthermore, reducing the number of surplus male calves aligns with animal welfare principles by ensuring that animals are bred and raised with a clear purpose and proper care [66].

Ethical considerations in sexing technology

The widespread adoption of fetal sexing technologies raises several ethical considerations, particularly regarding the manipulation of natural breeding processes. Critics argue that selectively determining the sex of offspring could lead to unintended consequences, such as the commodification of livestock and the potential for over-reliance on artificial reproduction methods. However, proponents of the technology emphasize that fetal sexing contributes to the overall health and welfare of livestock by reducing the number of unwanted male calves and improving the genetic quality of herds [2].

From an ethical standpoint, it is essential to balance the benefits of sexing technology with the need to maintain animal welfare standards. The technology should be used in a way that prioritizes the health and well-being of animals, ensuring that the breeding process is humane and that animals are treated ethically throughout their lifecycle. This includes providing adequate care for both male and female calves and ensuring that selective breeding does not compromise the overall diversity and resilience of livestock populations [95].

BARRIERS TO ADOPTION

Technical and financial constraints

One of the major challenges in implementing bovine fetal sexing in India is the limited access to advanced reproductive technologies in rural areas, where most dairy farming takes place. Despite significant advancements in technology, many farmers in rural and semi-urban areas lack the necessary infrastructure to utilize these tools. The availability of ultrasound equipment, PCR machines, and other diagnostic technologies is largely concentrated in urban centers or specialized veterinary clinics, making it difficult for small-scale and marginal farmers to access them. Moreover, the logistical challenges involved in transporting cattle to urban centers for sexing procedures further exacerbate this issue [52].

For instance, a pilot project in Uttar Pradesh's Bundelkhand region aimed to improve dairy herd genetics through sex-sorted semen technology. While

Table 3. Key barriers to the implementation of bovine fetal sexing in India.

Barriers	Impact	Mitigation Strategies	References
Limited access to technology	Reduces adoption rates in rural areas	Government subsidies for technology dissemination	[66]
High cost of equipment	Prevents small farmers from adopting	Financial support and low-interest loans	[74]
Lack of skilled professionals	Results in inconsistent and inaccurate results	Training programs for veterinarians and farmers	[36]
Outdated infrastructure	Leads to equipment malfunction and poor outcomes	Investment in rural infrastructure	[87]

the project achieved a conception rate of over 93% for female calves, it faced significant challenges due to inadequate infrastructure and high costs. The project involved over 7.5 lakh artificial inseminations, but the lack of local facilities and trained personnel in remote areas hindered its scalability and effectiveness [89].

Similarly, in Gujarat, Amul Dairy launched a mobile semen sorting laboratory to provide sex-sorted semen to farmers at subsidized rates. Despite the innovative approach, the initiative faced challenges related to the high cost of the mobile lab ($25 crore) and the need for specialized equipment and trained personnel. These factors limited the widespread adoption of the technology among small-scale farmers [75].

The high cost of importing such technologies also presents a barrier to their widespread adoption. Even in regions where technology is available, it is often outdated or not maintained properly, resulting in inconsistent outcomes for farmers. Furthermore, the lack of veterinary support services in remote regions limits the practical application of fetal sexing, as farmers need skilled professionals to operate these machines and interpret the results [82].

Skill development in rural areas

Another key issue is the lack of skill development and technical expertise (Table-3) among rural veterinarians and farmers. Bovine fetal sexing requires trained personnel to operate ultrasound machines or conduct DNA analysis. However, many veterinary professionals in rural areas are not equipped with the necessary training to perform these procedures. This skills gap prevents the effective use of available technologies and limits the potential for widespread adoption of fetal sexing in rural communities [74].

Additionally, there is a lack of training programs tailored to the needs of rural farmers, who are often unaware of the benefits and proper use of fetal sexing technology. The absence of a structured skill development framework at the local level restricts the growth of this innovative practice. While some government and private initiatives have started to address this issue, the progress is slow, and many rural regions remain underserved [95].

Financial and policy constraints

The cost of implementing fetal sexing technology is prohibitively high for small and marginal farmers, who make up a significant portion of India's dairy farming sector. Advanced techniques like PCR and FISH require expensive equipment and specialized reagents, driving up costs for individual farmers. Even ultrasound-based methods, which are relatively more affordable, still pose a financial burden when factoring in the cost of skilled labor and maintenance [45].

For many farmers, the return on investment from fetal sexing is uncertain, especially given the upfront costs. The lack of affordable financing options further limits their ability to adopt these technologies. While large-scale dairy operations may benefit from economies of scale, small farmers struggle to justify the expense without tangible short-term benefits. This financial constraint is a major factor impeding the widespread adoption of fetal sexing in India [81].

Policy framework and government support

The policy framework surrounding the implementation of reproductive technologies in India's dairy sector is still evolving. While there are government programs aimed at improving livestock productivity, there is a lack of specific policies that promote the adoption of fetal sexing technology. Current government initiatives, such as subsidies for artificial insemination under the Rashtriya Gokul Mission and

Table 4. Key strategies for expanding bovine fetal sexing technologies in India.

Strategy	Stakeholders Involved	Expected Impact	References
Government subsidies and incentives	Government, farmers	Lower cost of adoption, wider accessibility	[61]
Public-private partnerships	Government, tech firms, veterinarians	Improved infrastructure, better access	[44]
Training programs	NGOs, universities, farmers	Skill development, effective use of technologies	[28]
Research and innovation support	Research institutes, tech developers	New affordable technologies, scalable solutions	[86]

the National Programme for Bovine Breeding, could be expanded to include fetal sexing. These programs focus on enhancing the genetic quality and productivity of dairy cattle, and incorporating fetal sexing could significantly improve herd management and optimize breeding decisions [51].

However, these schemes currently do not extend to cover the costs associated with fetal sexing, leaving farmers without the necessary support to adopt this technology. Bureaucratic hurdles and inconsistent policy enforcement across states further complicate the process. In some cases, the absence of clear regulatory guidelines has led to the slow rollout of these technologies [29].

To overcome these barriers, it is recommended that a new subsidy line be created under existing artificial insemination initiatives specifically for fetal sexing trials. This forward-looking policy intervention could provide small and marginal farmers with the financial support they need to adopt fetal sexing technology. It would also incentivize research and pilot projects in rural areas to assess its viability, ensuring that the benefits of this technology reach a broader segment of the farming population. Until such measures are implemented, the technology will remain inaccessible to a large portion of India's dairy farming population [63].

Government and private sector collaboration will be crucial in overcoming these financial and policy barriers. Public-private partnerships could facilitate the establishment of more accessible veterinary services and the dissemination of technologies to underserved regions. Additionally, establishing more robust policy frameworks that include financial incentives for small farmers will ensure more equitable access to these critical reproductive technologies [86]. To unlock the full potential of fetal sexing technology, India must invest not just in tools but in training, trust-building, and targeted subsidies. An integrated approach—bridging rural infrastructure gaps, training youth, and tweaking policies–can democratize access and redefine the future of dairy farming.

STRATEGIC RECOMMENDATIONS FOR BROADER ADOPTIONS

Government interventions

The Indian government has a critical role to play in promoting advanced bovine sexing technologies. Government interventions in the form of subsidies and incentives can make these technologies more accessible, especially for small and marginal farmers who may struggle with the high costs associated with advanced reproductive technologies. For example, offering subsidies for equipment like ultrasound machines or PCR kits would lower the financial burden on farmers and veterinary clinics, making it easier for them to adopt these technologies [74].

In addition to direct subsidies, the government can also promote policies that encourage research and development in reproductive technologies. Tax incentives for companies developing affordable and scalable fetal sexing techniques could accelerate innovation in this area, ultimately benefiting the dairy industry as a whole. Establishing clearer guidelines and providing funding for pilot programs in rural areas would further boost the adoption of fetal sexing technologies across India [34].

Public-private partnerships

Public-private partnerships (PPPs) can help bridge the gap between technology providers and the livestock industry. Such collaborations can facilitate the development and dissemination of bovine sexing technologies on a larger scale. For instance, partnerships between the government, veterinary services, and private technology firms could lead to the creation of mobile diagnostic units that can provide fetal sexing services to remote rural areas [61].

Moreover, private sector investment in technology can help drive down the costs of fetal sexing, making it more affordable for farmers. By leveraging private sector expertise in advanced technologies, PPPs can also focus on training initiatives that ensure farmers and veterinarians have the skills needed to use these technologies effectively. These partnerships (Table- 4) could also address some of the technical challenges by providing better infrastructure for rural veterinary services [41].

Training and awareness programs

Training and awareness programs are essential for the successful implementation of bovine fetal sexing technologies. Farmers and veterinarians in rural areas need to be equipped with the necessary skills and knowledge to use advanced reproductive technologies effectively. Government initiatives, supported by both the private sector and NGOs, can organize training workshops and certification programs for veterinarians to operate ultrasound equipment and conduct DNA-based tests [75].

Increasing awareness among farmers about the economic and animal welfare benefits of fetal sexing is also vital. Educational campaigns, led by local agricultural extension services, can help demystify the technology and encourage more farmers to adopt it. Additionally, integrating these programs into existing rural development schemes would make it easier to reach a wider audience and ensure that both large-scale and small-scale farmers benefit from the initiative [52].

Technological innovation and research support

To ensure that bovine fetal sexing becomes more accessible and affordable, there is a need for continued innovation in the field. Encouraging research into scalable, cost-effective technologies will help address the financial and logistical barriers currently hindering widespread adoption. Collaborations between research institutes and private technology developers can foster the creation of new tools, such as portable ultrasound machines or improved non-invasive DNA testing kits that are specifically designed for rural settings [86].

Moreover, government funding for research and development (R&D) in agricultural technologies can significantly boost the production of localized solutions tailored to India's dairy industry. By focusing on affordability and scalability, researchers can develop innovations that allow small and marginal farmers to benefit from fetal sexing without the high costs typically associated with advanced reproductive technologies. This research should also focus on enhancing the efficiency of existing methods, making them more user-friendly and accessible to a wider range of farmers and veterinarians.

FUTURE PERSPECTIVE

Integration of AI and machine learning in fetal sexing

Artificial intelligence (AI) and machine learning (ML) are poised to revolutionize bovine fetal sexing by improving the accuracy and efficiency of ultrasound-based methods. AI algorithms can be trained to analyze ultrasound images and detect key markers for sex determination, reducing the dependency on human expertise. This technology has the potential to make fetal sexing more accessible to a broader range of farmers by offering faster and more reliable results [78].

Development of portable and cost-effective diagnostic tools

The development of portable and affordable diagnostic tools is another key area of innovation. Advances in miniaturization and non-invasive DNA testing technologies could lead to the creation of portable PCR machines or handheld ultrasound devices that are suitable for use in rural settings. These tools would significantly reduce the costs associated with fetal sexing and make the technology more accessible to small-scale farmers [65].

Potential for genetic manipulation and selective breeding

Genetic manipulation through techniques such as CRISPR has the potential to further enhance selective breeding programs in the livestock industry. By selectively modifying genes associated with sex determination or desirable traits, farmers could not only influence the gender ratio of their herds but also improve other key traits such as disease resistance and milk production. While still in the early stages of research, genetic manipulation offers exciting possibilities for the future of bovine breeding [94].

CONCLUSION

Bovine fetal sexing has the potential to transform India's dairy and livestock sectors by enhancing milk production, optimizing herd composition, and offering economic benefits. Selectively increasing the number of female calves enables farmers to focus on more productive herds, improving profitability and animal welfare by reducing the number of unproductive male calves. However, challenges such as high costs, limited access to advanced equipment, and lack of technical expertise hinder widespread adoption. Solutions, including government interventions, public-private partnerships, and training programs, are essential to overcome these barriers, particularly in rural areas. Advanced fetal sexing technologies not only improve farm profitability but also promote genetic advancements, leading to healthier, more resilient herds. This aligns with global trends towards sustainable and ethical farming by reducing surplus male calves, optimizing resource use, and allowing farmers greater control over reproductive outcomes. Continued research into affordable diagnostic tools, artificial intelligence, and genetic manipulation is vital for enhancing accessibility. Policy support through subsidies, financial incentives, and skill-building initiatives will be crucial for the widespread adoption of this technology.

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Cite this article as: Prasanth Kumar M, Murugavel K, Bindu Puspa M. Advancing bovine fetal sexing in India: strategic technological and policy perspectives - a review. Explor Anim Med Res. 2025; 15(1), DOI:10.52635/eamr/15.1.4-15.