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Artificial Insemination and Embryo Transfer: Emerging Technologies in the Livestock Industry

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***Abstract*— *Artificial insemination and embryo transfer have emerged as revolutionary technologies in the livestock industry, offering remarkable opportunities for genetic improvement and efficient herd management. In modern agriculture, these assisted reproductive technologies are increasingly being utilized for a wide range of applications, including out-of-season estrus induction, enhancement of reproductive performance, and preservation of endangered species or breeds. Nonetheless, significant advancements have been made in embryo technologies, particularly in the areas of estrus synchronization, superovulation, and in vitro embryo production. Incorporating applied reproductive technologies continues to effect animal production systems by providing producers opportunities to enhance genetics, reduce transfer of disease, advance fertility, and ultimately increase offspring value. Improvements in fertility and technology, reductions in cost, and improvements in ease of application will ensure that more cattle producers will adopt applied reproductive technologies in future years. However, incorporation of applied reproductive technologies into production systems will vary worldwide depending on cattle markets, infrastructure, production systems, and climate.*

***Keywords*— Artificial insemination, embryo transfer, reproductive technologies, genetic improvement, estrus synchronization.**

I. INTRODUCTION

Reproductive biotechnology, such as artificial insemination and embryo transfer, is essential in animal husbandry for transferring desired traits between different types of farm animals. This is especially crucial for animals that do not produce milk. With the expected rise in demand for meat, the use of reproductive biotechnology is necessary to meet this demand and ensure food security in India and worldwide. Selective breeding of high-quality females with desirable males from specific breeds and crosses within the Indian genetic architecture is crucial to meet the demand for healthier A2 milk and to breed superior female calves with a long and productive life.

The use of reproductive biotechnologies in any given breeding system is determined by the natural behaviors of the species concerned, as well as by what is practically feasible in the way of reproduction. These new reproductive advances provide the potential to manipulate early embryonic development in some way to enhance reproduction or production. Research involves using embryonic technology to create embryos from the best pedigree cattle and supervise the reproduction and development of those embryos to maximize the number of cows and bulls born. The major goal of this paper is to provide an in-depth review on artificial insemination and embryo transfer in the livestock industry. India has a vast resource of livestock and poultry, which plays a vital role in improving the socio-economic conditions of rural masses. There are about 303.76 Mn bovines (Cattle, Buffalo, Mithun, and Yak), 74.26 Mn sheep, 148.88 Mn goats, 9.06 Mn pigs and about 851.81 Mn poultry as per 20th Livestock Census in the country. In the current scenario, India is the largest producer of Milk and Buffalo Meat, the 2nd largest producer of Goat meat, 3rd in Egg production and the 8th largest in overall Meat Production in the world (Katoch, 2022) (Bankar *et al.*,) (Siripurapu *et al.*,2024) (Sharma & Shelly, 2023). Meat and milk from farmed animals including livestock (cattle, goat, and buffalo) and poultry are sources of high-quality protein and essential amino acids, minerals, fats and fatty acids, readily available vitamins, small quantities of carbohydrates and other bioactive components. Some poor countries may not be able to sustain these levels of meat and milk requirement, leading to malnutrition. (Rueda *et al.*,2024) (Tona, 2021) (Ponnampalam *et al.*,2022) (HE *et al.*,2021) Demand for meat and milk production is also expected to double in 2050 in developing countries, where population is expected to double (Latino *et al.*,2020) (Erdaw, 2023) (Van Dijk *et al.*,2021) (Humpenöder *et al.*,2022). Thus, to meet the requirement, increasing production, safe processing and marketing of meat and milk, and their products are big challenges for livestock producers. In that scenario Biotechnology is being an emerging field in various research and production field of livestock industry. It has the potential to improve the productivity of animals by increasing growth, carcass quality and reproduction, improving nutrition and feed utilization, improving quality and safety of food, improving health and welfare of animals, and reducing waste through more efficient utilization of resources. Therefore, Various biotechnology methods are being used in improving the breeding stock of animals. These include artificial insemination (AI), embryo transfer (ET), in-vitro fertilization (IVF), somatic cell nuclear transfer, and the emerging technology on somatic cell nuclear transfer.

Artificial insemination is by far the most widely used biotechnology in animal reproduction and has been reported to result in genetic progress that is four times better than natural mating. Artificial insemination (AI) and embryo transfer (ET) are probably the most popular methods that have been adopted in developed and developing livestock industries. Especially since the development of efficient semen freezing methods, Artificial insemination has become the most widespread biotechnology applied to livestock and especially cattle production. AI has allowed for the implementation of the progeny-testing scheme prevalent particularly in dairy cattle production, and which has had a major impact on the improvement of the herd by increasing the accuracy of selection despite the associated increase in generation interval. Supporting technologies that have increased the efficiency of AI and ET include micromanipulation of gametes and embryos for splitting, sexing, cloning, gene transfer, cryo-preservation of embryos, in-vitro maturation, fertilization, and culture (IVFMC) as well as genome analysis. The recent advances in biotechnology in reproduction also include production of transgenic animals and cloning (Said *et al.*,2020) (Arain *et al.*,2023) (Funahashi2020) (Das *et al.*,2022).

Although Embryo transfer technology presently not economically feasible for commercial use on small farms, moreover embryo technology can greatly contribute to research and genetic improvement of local breeds. Advances in this area are mainly applicable in cattle. There are two procedures presently available for production of embryos from donor females. One consists of superovulation, followed by AI and then flushing of the uterus to gather the embryos. The other, called in vitro fertilization (IVF) consists of recovery of eggs from the ovaries of the female then maturing and fertilizing them outside the body until they are ready for implantation into foster females. The principal benefit of embryo transfer is the possibility to produce several progenies from the female, just as AI produces many offspring from one male animal (Mueller & Van Eenennaam, 2022) (Daly *et al.*,2020) (Hansen, 2020) (Ferré *et al.*,2020) (Fesahat *et al.*,2020) (Baruselli *et al.*,2020).

1.1 Background and Significance

In the field of animal sciences, particularly in animal reproduction and breeding, artificial insemination and embryo transfer are considered to be significant technologies of the 20th century. Artificial insemination in domesticated farm animals was first demonstrated in the dog in 1780, and the first calf was born from embryo transfer in the rabbit (Sikka & Atheya, 2022) (Mukherjee *et al.*,2023). The successful application of these two biotechnologies in recent decades has had an unprecedented impact on genetic improvements of livestock and domesticated species. Increased reproductive performance has been observed in animals since then, particularly in relation to the amount of sperm and embryos produced per animal per year. (Verma *et al.*,2022)

Reproductive management naturally influences the genetic pool of domestic breeds and has a direct effect on animal productivity and meat and milk quality. Reports from various countries have shown that the influence of embryo transfer programs in cattle is rapidly reflected in their genetic gains. Artificial insemination and embryo transfer address livestock from the point of view of reproductive efficiency, which plays a decisive role in animal breeding. Sub fertile animals are responsible for serious economic losses due to reproductive failure and early culling. The organization on food and agriculture reported that a large amount of cattle genetic material was sent abroad by various regions. These areas have a large market share of livestock, mainly sheep, goats, and bovines (Mebratu *et al.*,2020).

Artificial insemination (AI) and embryo transfer (ET) are pivotal technologies in modern livestock breeding, significantly enhancing genetic improvement and reproductive efficiency. These advanced reproductive technologies (ART) facilitate the rapid propagation of superior genetic traits across herds, thereby improving overall productivity.

Key Statistics and Trends

Conception Rates:

The conception rate after AI or ET is a critical metric for evaluating breeding methods. Studies indicate that combining AI with ET can yield higher pregnancy rates compared to AI alone, with some reports showing up to 61.9% pregnancy success when both methods are utilized together (Bortoluzzi, E. M. *et al*., 2024).

Production Data:

A comprehensive analysis from a large dataset involving over 2.5 million animal records revealed that: 95.68% of lactations were from AI, while only 0.23% were from IVF, indicating the predominance of AI in current practices. The use of MOET accounted for approximately 4.09% of lactations (Lafontaine, Simon *et al*., 2023).

Embryo Production Growth:

Since 2017, the number of embryos produced via IVF has surpassed those produced through traditional flushing techniques, highlighting a shift towards more efficient embryo production methods (Mikkola, M. *et al.*,2024).

Genetic Progress:

The integration of genomic assessments with ART allows for the identification of animals with high genetic potential at an early age, potentially achieving about seven years' worth of genetic progress in just one year through selective breeding practices (Mikkola, M. *et al.*,2024).

Economic Impact:

The economic advantages of these technologies are substantial, as they allow for the introduction of superior genetics into herds at a lower cost and with enhanced biosecurity measures (Mikkola, M. *et al*.,2024).

Advantages of ART

Increased Offspring Production: ART enables superior females to produce multiple offspring in a shorter timeframe compared to traditional breeding methods.

Genetic Diversity: Facilitates the introduction of diverse genetics into herds, which can enhance resilience and adaptability.

Improved Reproductive Efficiency: Technologies like ovum pickup and embryo freezing allow for flexible breeding schedules and improved synchronization among recipient animals (Mikkola, M. *et al.*, 2023).

The adoption of artificial insemination and embryo transfer technologies is revolutionizing livestock breeding by improving genetic quality and reproductive efficiency. As these technologies continue to evolve, they promise to play an even more significant role in shaping the future of livestock production globally.

II. HISTORY OF ARTIFICIAL INSEMINATION AND EMBRYO TRANSFER

The history of artificial insemination and embryo transfer dates back to the early 20th century, when scientists began experimenting with ways to improve breeding practices in livestock. Artificial insemination and embryo transfer have revolutionized the livestock industry by allowing for more controlled breeding practices. These emerging technologies have the potential to greatly improve genetic diversity and overall livestock health (Houston *et al.*, 2020) (Brito *et al.*, 2021) (Neethirajan & Kemp, 2021). Artificial insemination and embryo transfer have been significant advancements in the livestock industry, revolutionizing breeding practices and genetic selection. The history of artificial insemination is reported as with the first successful artificial insemination in livestock in 1949 with dairy cattle (Sharma *et al.*,2024) (Bruno, 2022) (Shanku, 2023).

III. TECHNOLOGICAL ADVANCEMENTS IN ARTIFICIAL INSEMINATION

Since the advent of genetics, IART has been an increasingly powerful tool in livestock industries. Technological advancements have since revolutionized the development of AI, facilitating the evolution of cryopreservation protocols to enhance sperm quality and potential cryoresistance at different developmental stages of livestock. Several researchers have continuously optimized the procedure of IART to improve associated productivity. Additionally, the application of air-dropping fresh and cryopreserved spermatozoa after uterine expulsion or transfer to the oviduct, or superovulatory flooding of sperm cells in the genital tract, has in many ways eliminated the critical limitations of reproductive technologies. Furthermore, numerous research findings have facilitated the application of donor inseminated AI and unique short-term fertility tests of sires and males, blind sperm evaluation, and selection procedures because of the capability of oviductal sperm selection and removal of immotile or abnormal spermatozoa using in vitro or in vivo setups (Animal *et al.*,2020) (Mackenzie and Kyriazakis2021) (Bassey, 2021) (Stucki, 2023).

The development of different modern AI technologies has significantly enhanced the productivity of livestock industries by changing IART from a potential animal welfare concern to a less invasive AI procedure. These essential integrations of science and technology between reproduction specialists have drastically reshaped the mechanisms of AI and sperm cryostorage, the conventional AI technique used to improve the productivity of livestock. Additionally, more than 70 million livestock were artificially inseminated in the same year, in line with the assertion that artificial insemination is the safest way to improve the productivity of animals (Quelhas *et al.*,2023) (Panda *et al.*,2021) (Seidel Jr & DeJarnette, 2022). Art has revolutionized all aspects and transferred IART into an increasingly high-tech, high-impact AI.

IV. TECHNOLOGICAL ADVANCEMENTS IN EMBRYO TRANSFER

One of the key technological advancements in embryo transfer is the use of cryopreservation techniques to store embryos for future use. One of the key technological advancements in embryo transfer is the use of cryopreservation techniques to store embryos for future use. This method has revolutionized the livestock industry by allowing breeders to preserve genetic material and ensure the future of their herds. Technological advancements in embryo transfer have greatly improved the efficiency and success rates of breeding programs in the livestock industry. One of the key technological advancements in embryo transfer is the use of sexed semen to improve the gender selection process in breeding programs. Recent advancements in sexed semen technology have revolutionized the breeding industry by allowing for more precise gender selection in livestock. One of the key technological advancements in embryo transfer is the use of in vitro fertilization (IVF) techniques to improve success rates (Aljaser, 2022) (Kumar *et al.*,2022) (Khan *et al.*,2021) (Sharma *et al.*,2021) (Valente *et al.*, 2022) (Tharasanit & Thuwanut, 2021) (Sharafi *et al.*,2022).

V. BENEFITS OF ARTIFICIAL INSEMINATION AND EMBRYO TRANSFER IN LIVESTOCK INDUSTRY

Artificial insemination (AI) and embryo transfer (ET) have made significant strides in the livestock industry over the past two decades, with potential applications in producing recipients, the use of sexed semen, reproductive biotechnologies, and the creation of genetically modified animals. Several benefits exist in using AI and ET in the livestock industry. The use of AI and ET enables animal breeders, producers, and farmers to select and reproduce superior female animals and sires, which will have direct effects on genetic improvement. By selecting proven breeding stock through technological means such as AI and ET and superior male-female combinations, genetic improvement takes a giant step forward. The use of sexed semen also adds a bonus in terms of increased milk production and desirable female characteristics. The reduction of unwanted or less desired bull calves for the beef industry using sexed semen has also been reported. AI, in combination with induced estrous cycles in the dairy industry, permits flexible and improved herd management for ideal husbandry care, including scheduling of age and appropriate milk production and extended milk production patterns in early lactation cows (Varshney *et al.*,2021) (Razzaq *et al.*,2021). AI is also a practical and cost-effective method to introduce desirable traits into dairy herds when farmers or breeders have minimal farm facilities. Interestingly, the use of AI and ET in the livestock industry increases the financial wealth of farmers or breeders by reducing the costs in herd management, which are known to negatively impact their businesses (Singh *et al.*,2021) (Monteiro *et al.*, 2021) (Akhigbe *et al.*,2021) (Javaid *et al.*, 2023). Finally, animal welfare can be improved using breeding methods due to genetic selection based on reproductive biotechnologies such as AI and ET. Moreover, animal welfare is one of the critical purchasing factors in today's world. Sustainable animal breeding, together with technological improvements, is crucial in evolving methods to facilitate food security and reduce the impact of livestock rearing on the environment. Often, reduced maintenance costs, mainly herd-replacement costs due to genetic improvement, are expected to yield positive economic returns. In contrast, farmers and producers are encouraged by substantial economic gains as a result of optimal breeding strategies using AI and ET. Generally, AI and ET are of expanding importance in African countries and can make major contributions to livestock development.

VI. CHALLENGES AND LIMITATIONS

Despite several advantages to both technologies, both AI and ET are not without limitations or challenges. AI success rates are strongly affected by cryopreservation of semen, with variable results across different livestock species. Moreover, technical expertise and facilities are required even for AI in domestic animals. Embryo transfer also has variable success rates, with newer cryopreservation methods being far less successful than working with fresh or in vivo produced embryos, particularly in pigs. Further, the complexities enforce procedural costs, making it too expensive for some farmers to consider. Other technical issues with embryo transfer are that it requires labor and time, and, especially for international programs, comes with trade restrictions and quarantine regulations. More generally, both embryo transfer and artificial insemination require a certain level of knowledge, infrastructure, and technical expertise or training. This limits less developed countries in their take-up (Zuidema *et al.*, 2021) (Koch *et al.*,2022) (Pardede *et al.*,2020) (Boneya, 2021).

Financial and human resources are major limitations, particularly in developing countries. A second challenge, likely to affect societies with greater access to advanced breeding technologies more than the less developed ones, is a growing level of ethical and environmental concern about animal welfare and genetic manipulation. Regulation can also act to limit the use of such technologies, either explicitly or by mandating excessively high standards that are effectively unachievable. Other issues that are inherent to both AI and ET in farmed animal populations are the loss of genetic diversity, with its attendant risks to adaptability, and an increase in genetic or familial trends for common disease conditions which could provide an increased risk. Yet any of these traits can be reduced in frequency as genetic technologies mature (Jahanger *et al.*,2022) (Usman *et al.*,2022) (Khan & Ozturk, 2021) (Haakenstad *et al.*,2022) (Rahim *et al.*,2021). Overall, this section will not try to seek solutions to each of these concerns. Rather, it will highlight what might presently be seen as barriers to the increased use of advanced breeding technologies and allow consideration of ways to address the concerns in the future.

VII. ETHICAL AND LEGAL CONSIDERATIONS

Society's perception of AI and ET as ethically acceptable technologies is reflected in the growth of the AI and ET industries over the last century. However, as the population's belief focus changes, so do the ethical principles governing social behavior, including the ethics of these reproductive technologies. The use of genetic material from inbred and infertile animals, who cannot live a healthy life, raises ethical issues as it provides a "selection filter" for which animals are allowed to breed, raising the concern about the definition of an animal's right to live. As our understanding of AI and ET has grown, so have the concerns about the welfare of the animals who are part of these reproductive technologies. The alleviation of an animal's suffering is a moral obligation, and this should inform technological advancements that promote AI and ET. A breach of guidelines established by laws regulating ethical practice of AI and ET within animals may result in the removal of consent to use these ARTs and of laws that directly regulate AI and ET. (Quartuccio *et al.*,2020) (Seidel2020) (Engdawork *et al.*, 2024) (Hart-Johnson & Mankelow, 2022)

Comparison of legal documents across the globe found no country adheres to the same AI and ET guidelines. Enforcement of the policy is crucial for implementing the AI and ET ethical principles. They must therefore follow ethics set by international and national government law as well as those developed by industries, researchers, veterinarians, and animal breeders. There is also a growing market of breeders who are environmentally ideologizing their AI and ET services, showing a clear stakeholder concern with environmental ethics. (Daly *et al.*, 2022) (ÓhÉigeartaigh *et al.*,2020).

VIII. COMPARISON WITH NATURAL BREEDING METHODS

When comparing artificial insemination and embryo transfer with natural breeding methods in the livestock industry, it is evident that these emerging technologies offer numerous advantages in terms of genetic improvement, disease prevention, and overall production efficiency. For example, artificial insemination allows for the use of superior genetics from a few elite animals to be spread more widely throughout a herd, leading to significant improvements in overall herd quality. In contrast, natural breeding methods rely on the mating of animals within the same herd, which may limit the genetic diversity and overall quality of the offspring. In contrast, emerging technologies in the livestock industry such as artificial insemination and embryo transfer offer a wider range of genetic diversity and can improve the overall quality of the offspring. When comparing artificial insemination and embryo transfer with natural breeding methods in the livestock industry, it is evident that these emerging technologies provide a wider range of genetic diversity, leading to an overall improvement in the quality of the offspring. Additionally, they offer increased control over breeding outcomes and can help in the selection of desirable traits. (Brito *et al.*,2021) (Salgotra & Chauhan, 2023) (Houston *et al.*,2020) (Vaintrub *et al.*,2021).

IX. APPLICATIONS IN DIFFERENT LIVESTOCK SPECIES

The use of artificial reproduction techniques in domestic animals such as cattle, sheep, and goats has increased over the past few decades. It has now become an essential tool in the cattle industry because of the increased genetic improvement, selective breeding of species, and the potential to enhance the introduction of superior germplasm from different regions for genetic improvement of depleted populations worldwide. These assisted reproductive techniques are suitable for use in a variety of farming systems, including smallholder and commercial. To achieve optimum results with the different techniques, such as artificial insemination and embryo transfer, it is essential to have a good understanding of the reproductive characteristics of the animal, particularly the female germplasm, such as estrous patterns.

Each livestock species has specific reproductive characteristics, which influence the applicability of different reproductive techniques. A few examples of artificial insemination and embryo transfer of some selected mammalian species will be discussed, including cattle, sheep, goats, pigs, deer, and Cape buffalo. In sheep, long-term storage of oocytes and their in-vitro applications as a valuable reproductive tool in many facets of biology and medicine, such as studies about storage of tissues and organs for the possible future generation of animals with valuable alleles and genotypes, are noted. Artificial insemination and embryo transfer are applied worldwide in cattle. Both techniques have gained a lot of knowledge in the last few decades, resulting in increased technical knowledge and success in the development of both artificial insemination and embryo transfer. Furthermore, artificial insemination in cattle has been commercialized, and a large number of companies worldwide produce semen and provide technical expertise related to the procedures. These new techniques have given livestock producers an opportunity to access superior genetics from livestock breeding programs, increasing the genetic pool and allowing for genetic gains to be made in some countries (Mebratu *et al.*,2020) (Hansen, 2020) (Baruselli *et al.*,2020).

X. ECONOMIC IMPACT IN THE LIVESTOCK INDUSTRY

Artificial insemination (AI) and embryo transfer technologies have made significant headway in genetic improvements and will continue to play important roles in the future. Substantial financial benefits have steadily attracted many reproductive physiologists to strategically focus on this area of research, as profit potential is a major driving force in commercial livestock production and genetic advancements. Clearly, the adoption and rate of utilization of such technologies decreased the overall production costs, thus increasing profits. However, one of the only ways to influence an industry's reproductive extent can be through economic means (Singh & Singh, 2022) (DeCherney *et al.*,2022) (Singer *et al.*,2021).

It has long been established that in both AI and ET, financial benefits are possible via improved pregnancy rates. In the case of AI, elevated pregnancy rates using superior sires are made possible, presenting the potential to increase financial revenue by as much as twenty times the original seedstock bank. Moreover, the progeny is generally able to achieve much higher annual profit margins of more than ten times per seedstock. Upon commercial company entry, such trends become even more predominantly obvious, with the further potential to increase annual profit margins by as much as 10–15% through the elimination of problematic genetic traits and gene carriers. Differing market trends can have significant financial implications for a company, in the success of producing higher profitability or, by logical analysis, negative consequences. Though a quick cash injection it may be, AI and ET must be seen as long-term investments. This is because the initially high semen prices, for instance, will, through a systematic deployment strategy, decrease, thus increasing the gene pool, which can also further benefit commercial producers. Additionally, profit margins can increase dramatically when a company also takes advantage of reducing disease prevalence by using reproductive technologies. Over the long term, in addition to the economic incentives, other long-term benefits in utilizing one of the technologies are the decreased costs associated with increasing productivity by eradicating animal disease, efficiency, parasitism, and other animal welfare issues, in turn ultimately contributing to the reduction of industry disease-related expenditure and improvement of national stock. Therefore, this must be developed as a cohesive strategic plan including a multi-faceted approach between government, commercial companies, and breeding companies alike to have the most impact at a national level in production animals (Davidson & Boland,

2021) (Davidson and Boland2020) (Medenica *et al.*,2022).

XI. FUTURE TRENDS AND INNOVATIONS

The livestock industry is on the brink of a major transformation, thanks to new developments in genetic selection, reproductive technologies, and data analytics. Artificial insemination and embryo transfer technologies are set to revolutionize the industry, leading to increased efficiency and genetic improvement. One potential future trend in artificial insemination and embryo transfer technologies in the livestock industry is the use of advanced genetic selection techniques to further enhance desirable traits in livestock populations. One example of advanced genetic selection techniques in the livestock industry is the use of marker-assisted selection to improve disease resistance and overall health in livestock populations. In the future, artificial insemination and embryo transfer technologies are expected to become even more advanced, allowing for greater precision and efficiency in breeding programs. Some potential future advancements in artificial insemination and embryo transfer technologies include the use of gene editing techniques to enhance desired traits in livestock.

XII. CONCLUSION AND FUTURE DIRECTIONS

To sum up, the progress made in artificial insemination and embryo transfer technologies has completely transformed the livestock industry, resulting in better breeding effectiveness and a wider range of genetic characteristics. Moving forward, further advancements in artificial insemination and embryo transfer technologies are expected to revolutionize the livestock industry even more. This includes the potential for increased efficiency, genetic diversity, and overall productivity. In conclusion, the implementation of artificial insemination and embryo transfer technologies in the livestock industry is expected to continue advancing, leading to improved efficiency, genetic diversity, and overall productivity. Moving forward, further research and development in this area will be crucial for maximizing the potential benefits of these emerging technologies.

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