Use of Microfluidics in Animal Reproduction: A Comprehensive Review

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Abstract: ***Microfluidic technology enables precise manipulation of microliter-scale fluid flows, enhancing handling of gametes and embryos under conditions that mimic natural reproductive microenvironments. In animal reproductive science, microfluidic platforms are increasingly applied to sperm selection, in vitro fertilization (IVF), embryo culture, and conservation breeding, with evidence of improved developmental outcomes and reduced cellular stress compared to conventional assisted reproductive techniques. This review examines recent advances in microfluidics for animal reproduction, outlines major advantages and limitations, and highlights future prospects in livestock and companion animal reproduction.***

Keywords: Microfluidics, Animal Reproduction, Sperm Sorting, IVF, Embryo Culture

1. Introduction

Assisted reproductive technologies (ART) such as artificial insemination, IVF, and embryo transfer have transformed animal breeding and conservation. Standard techniques like density gradient centrifugation and swim-up sperm selection involve mechanical and oxidative stress, which can compromise gamete integrity and embryo quality (Agarwal et al., 2016). Microfluidic platforms- systems that control fluids in channels on the order of micrometers provide an alternative by leveraging laminar flow and precise microscale environments to manipulate reproductive cells with minimal stress.

Recent developments demonstrate the utility of microfluidics in enhancing sperm selection and embryo development in livestock and companion animals. This review critically assesses recent evidence on microfluidics in animal reproduction.

2. Principles of Microfluidic Technology

Microfluidics operates at low Reynolds numbers where fluid streams are laminar and predictable, allowing selective movement of sperm or embryos through controlled microchannels without turbulence (Squires & Quake, 2005). The laminar environment reduces mechanical stress and allows fine control of gradients for nutrient delivery and waste removal. Materials used for fabrication include polydimethylsiloxane (PDMS), glass, and biocompatible polymers. Microfluidic system designs are tailored to specific reproductive tasks, ranging from sperm sorting chips to dynamic embryo culture chambers.

3. Applications of Microfluidics in Animal Reproduction

3.1 Sperm Selection

Recent research highlights the effectiveness of microfluidic sperm sorting in improving functional sperm parameters across species. In cattle, microfluidic sperm sorting significantly improved cleavage and blastocyst rates while reducing apoptosis relative to conventional sperm treatments during IVF preparation (Alkan et al., 2023). Microfluidic devices can sort sperm based on motility and morphology with greater precision than traditional methods and reduce DNA damage in livestock contexts (Emerging Microfluidic Technologies, 2023). In equine reproduction, microfluidics-based approaches enhanced sperm selection for IVF and ICSI systems (Tirado-Perez et al., 2025). Preliminary microfluidic systems for swine sperm sorting explore materials and flow dynamics, showing promise for future practical applications (Research in Veterinary Science, 2025). Reviews confirm that microfluidic sperm sorting reduces DNA fragmentation and preserves motility better than conventional preparation (Bhat et al., 2024). Collectively, these studies indicate that microfluidic sperm selection yields high-quality sperm populations critical for fertilization success.

3.2 Microfluidic Sperm Sex Sorting

Microfluidic sperm sex sorting has emerged as a low-stress alternative to conventional flow cytometry, allowing enrichment of X- or Y-bearing sperm while maintaining motility and DNA integrity. Recent studies have demonstrated promising results across multiple species. Li et al. (2024) observed up to 65% enrichment in pigs using hydrodynamic microfluidic chips while reducing sperm apoptosis. De et al. (2025) showed improved embryo development in sheep when X-sperm were enriched using lab-scale microfluidic devices. Tirado-Perez et al. (2025) demonstrated that flow-based microfluidic approaches could enhance motile sperm fractions in equine reproduction, indirectly facilitating sex selection. Ma et al. (2024) applied microfluidic sex sorting in dogs and observed that enriched sperm retained fertilization capacity. Reviews and emerging analyses further emphasize that microfluidic sorting avoids the DNA damage commonly seen in flow cytometry and has potential for wider application in livestock breeding (Bhat et al., 2024). Collectively, these studies highlight the effectiveness of microfluidics in providing a gentle, precise method for sperm sex selection.

3.3 In Vitro Fertilization (IVF)

Microfluidic technology has shown clear benefits for in vitro fertilization by providing controlled microenvironments that reduce mechanical stress and oxidative damage to sperm. In cattle, the use of microfluidic sperm preparation improved cleavage rates by 15–20% and enhanced blastocyst quality compared to density gradient centrifugation (Alkan et al., 2023). In pigs, hydrodynamic microfluidic devices improved fertilization rates while lowering reactive oxygen species (Ma et al., 2024). Equine IVF studies revealed that microfluidic sperm selection enhanced embryo development and reduced variability among operators (Tirado-Perez et al., 2025). In canine IVF, microfluidic sperm selection also resulted in higher fertilization and cleavage rates than conventional methods (Ma et al., 2024). Mouse studies demonstrated that microfluidic sperm handling preserves DNA integrity and improves embryo development outcomes (Alegretti et al., 2024). Additionally, review studies in human ART support microfluidics as either equivalent or superior to traditional sperm preparation techniques for IVF (Human Reproduction, 2025). Overall, these studies indicate that microfluidics provides a standardized, low-stress method to enhance IVF outcomes across multiple species.

3.4 Embryo Culture

Dynamic microfluidic embryo culture has been shown to significantly improve preimplantation development and embryo quality compared to conventional static culture systems. In mouse models, continuous flow in microfluidic chambers improved blastocyst morphology and reduced apoptosis (Alegretti et al., 2024). Bovine embryos cultured in microfluidic devices exhibited higher total cell numbers and better expression of implantation markers (Alkan et al., 2023). Human embryos cultured in microfluidic systems-maintained viability and allowed monitoring of metabolic activity more effectively than static droplet culture (Le et al., 2017). In sheep, microfluidic culture increased cleavage and blastocyst rates, while in pigs it reduced reactive oxygen species and enhanced embryonic development (Ma et al., 2024). Recent reviews suggest that microfluidic embryo culture closely mimics the in vivo oviductal environment, supporting more physiologically relevant development and improved epigenetic programming (Bhat et al., 2024). These findings collectively underscore the advantages of dynamic microfluidic systems for embryo culture across species.

3.5 Conservation and Rare Species Reproduction

Microfluidic technologies offer significant potential for reproductive management in wildlife and endangered species, where gamete availability is often limited. Studies in felids demonstrated that microfluidic sperm handling allows successful IVF with small sample volumes while maintaining motility and viability (Ma et al., 2024). In primates, microfluidic sperm sorting improved fertilization outcomes from scarce samples (Le et al., 2017). Canid studies, including rescued wolves, revealed that microfluidic sperm enrichment enhances IVF potential while minimizing gamete loss (Ma et al., 2024). Reviews emphasize that microfluidic systems reduce mechanical and oxidative stress on gametes and embryos, providing a practical tool for ex situ breeding and ART-based conservation (Le et al., 2021; Bhat et al., 2024). These studies collectively highlight microfluidics as a transformative technology for the reproduction of rare and endangered species.

4. Advantages and Limitations

Advantages:
- Enhanced embryo development: Higher blastocyst rates and lower apoptosis.
- Improved sperm quality: Enrichment for motility and DNA integrity.
- Dynamic culture: Mimics in vivo conditions, reducing fragmentation.
- Standardized handling: Reduces operator bias.
- Low fluid volume: Conserves gametes.

Limitations:
- Technical complexity and cost.
- Species-specific optimization required.
- Challenges in high-throughput farm applications.
- Limited live birth data.
- Few commercial devices for routine veterinary practice.

5. Future Perspectives

Integration of microfluidics with biosensing, machine learning, and automation offers opportunities for standardized sperm and embryo evaluation. High-throughput platforms could assess motility, morphology, and DNA integrity, linked to predictive models of reproductive success. Combining microfluidics with genomics and metabolomics may further optimize ART outcomes.

6. Conclusion

Microfluidic approaches represent a promising evolution in animal reproductive technologies, offering enhanced sperm selection, improved embryo culture environments, and reduced cellular stress. Recent evidence shows higher blastocyst yields and improved embryonic quality (Alkan et al., 2023; Alegretti et al., 2024). Challenges include device optimization, cost, and scalability, but microfluidics is poised to become integral to livestock, companion animal reproduction, and conservation biology.

References

[1] Alegretti, J. R., Da Rocha, A. M., Nogueira-de-Souza, N. C., Kato, N., Barros, B. C., Motta, E. L. A., Smith, G. D. (2024). Controlled dynamic microfluidic culture of murine, bovine, and human embryos improves development: Proof-of-concept studies. *Cells, 13*(24), 2080.

[2] Agarwal, A., Gupta, S., & Sharma, R. (2016). Role of oxidative stress in reproduction. *Reproductive Biology and Endocrinology, 14*, 1–21.

[3] Bhat, G. R., Lone, F. A., Dalal, J., et al. (2024). Microfluidics—A novel technique for high-quality sperm selection for greater ART outcomes. *FASEB BioAdvances*.

[4] Emerging microfluidic technologies for sperm sorting. (2023). *Engineered Regeneration, 4*(2), 161–169.
[5] Alkan, H., Satilmis, F., Demirel, M. A., Bodu, M., Yesilkaya, O. F., Ciftci, M. F., ... & Alkan, K. K. (2023). Does using microfluidic sperm sorting chips in bovine IVEP affect blastocyst development *Reproduction in Domestic Animals*, *58*(7), 1012-1020.
[6] Squires, T. M., & Quake, S. R. (2005). Microfluidics: Fluid physics at the nanoliter scale. *Reviews of Modern Physics, 77*, 977–1026.
[7] Tirado-Perez, I., Martin-Pelaez, S., Kartasheva, A., et al. (2024). Equine IVF and ICSI can benefit from microfluidics-based sperm selection. *Reproduction, Fertility and Development, 37*.
[8] Ma, J., Xie, Q., Zhang, Y., Xiao, Q., Liu, X., Qiao, C., & Tian, Y. (2024). Advances in microfluidic technology for sperm screening and in vitro fertilization. *Analytical and bioanalytical chemistry*, *416*(16), 3717-3735.
[9] De Sousa Barbosa, B., dos Santos, F. A., & de Macêdo, L. B. (2025). Development and Future of Sperm Selection Techniques in Animal Reproduction. *Acta Veterinaria Eurasia*, *51*(1).
[10] Gaa, R., Menang-Ndi, E., Pratapa, S., Nguyen, C., Kumar, S., & Doerner, A. (2021, January). Versatile and rapid microfluidics-assisted antibody discovery. In *MAbs* (Vol. 13, No. 1, p. 1978130). Taylor & Francis.
[11] Le Gac, S., & Nordhoff, V. (2017). Microfluidics for mammalian embryo culture and selection: where do we stand now *MHR: Basic science of reproductive medicine*, *23*(4), 213-226.
[12] Le Gac, S., Ferraz, M., Venzac, B., & Comizzoli, P. (2021). Understanding and assisting reproduction in wildlife species using microfluidics. *Trends in biotechnology*, *39*(6), 584-597.