Review Report

The future of theriogenology: advancing research, clinical innovation, and education

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Abstract

Theriogenology, the veterinary discipline focused on animal reproduction, is undergoing rapid transformation, driven by innovations in biotechnology, artificial intelligence and global health integration. This review explores the future of theriogenology through 4 key dimensions: research, teaching, outreach, and ethics. In research, cutting-edge technologies (e.g. clustered regularly interspaced short palindromic repeats, gene editing, multiomics, and artificial intelligence-enhanced diagnostics) are reshaping fertility management, reproductive efficiency and species conservation. In education, immersive simulations, hybrid learning models and interdisciplinary curricula, are preparing future practitioners with technical skills and ethical frameworks needed for modern clinical and research environments. Outreach efforts are expanding the field's impact, bringing reproductive technologies to underserved communities, supporting wildlife conservation, and contributing to 'One Health' initiatives. However, these advancements raise complex ethical and regulatory challenges, including concerns regarding genetic modification, equitable access and cross-border collaboration. Addressing these issues will require global cooperation, capacity-building and a commitment to responsible innovation. Theriogenology's future lies not only in scientific progress but also in its ability to bridge disciplines and communities for the benefit of animals, ecosystems and society at large.

Keywords: Animal reproduction, reproductive biotechnology, veterinary education, One Health, ethics, assisted reproductive technologies, global outreach

Introduction

Theriogenology, the branch of veterinary medicine dedicated to the study and management of animal reproduction, stands at a pivotal juncture. Derived from the Greek words 'therio' (meaning beast) and 'gen' (creation, generation), theriogenology encompasses a wide range of disciplines, including obstetrics, gynecology, andrology, endocrinology, reproductive surgery, immunology, epidemiology, reproductive pathology, and assisted reproductive technologies (ART). Traditionally focused on improving fertility, managing reproductive disorders and assisting in breeding programs, the field now has an increasingly critical role across a broad spectrum of domains. These include optimizing livestock productivity to meet growing global food demands, ensuring reproductive health of companion animals, preserving genetic diversity in endangered wildlife,[1,2] and contributing to biomedical research through animal models. As the global population expands and environmental pressures intensify, the importance of theriogenology will assuredly only deepen.

In the coming decades, theriogenology is poised for a profound metamorphosis, driven by rapid technological innovation. Advances in technologies such as point-of-care, population care, precision gene editing, artificial insemination, and in vitro fertilization (IVF) are reshaping how fertility challenges are addressed. Simultaneously, integration of big data analytics and artificial intelligence (AI) is transforming diagnostics and reproductive management, enabling more precise and individualized interventions.[3] Education within the field is also evolving; immersive tools (e.g. virtual reality simulations, hybrid learning models) are revolutionizing how future veterinarians acquire theoretical knowledge and

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Citation: Clinical Theriogenology 2026, 18, 13365, http://dx.doi.org/10.58292/CT.v18.13365

hands-on skills.[4] These educational innovations will prepare students not only to excel clinically but also to navigate complex ethical considerations and conservation challenges.

This review explores how future research and teaching in clinical animal reproduction will evolve in tandem, with goals of elevating reproductive practices, empowering the next generation of theriogenologists and promoting animal welfare and biodiversity conservation worldwide.

Research: technological frontiers in reproductive science

Theriogenology, the science of animal reproduction, is undergoing a dramatic evolution driven by rapid technological advances. Historically rooted in classical veterinary obstetrics, gynecology and andrology, the field now intersects with molecular biology, bioengineering, data science, and conservation. Emerging innovations are transforming how reproductive disorders are diagnosed and treated, how fertility is enhanced or preserved and how species, both domestic and wild, are sustained for future generations. Below is an overview of key technological frontiers reshaping research in clinical animal reproduction.

Reproductive technologies

The future of reproductive interventions in animals lies in integration of precision biotechnology into ARTs. Advanced procedures, including IVF and intracytoplasmic sperm injection, once limited to select species like humans and horses, are being refined for broader use in livestock,[5,6] companion animals,[7] and even endangered wildlife.[8,9] These technologies facilitate controlled breeding, allow selective trait propagation and assist in overcoming infertility related to genetic, anatomical, or hormonal issues.

Another substantial leap is in vitro gametogenesis, a technique involving generation of functional gametes (sperm or ova) from stem cells.[10,11] This technology holds much promise, not only for preserving valuable genetics from individuals unable to breed naturally but also for enabling reproductive continuity in rare or endangered species.[12] Similarly, development of in vitro testicular organoids[13,14] and ovarian organoids[15] allows researchers to simulate reproductive environments for studying gametogenesis, toxicology and reproductive disorders in a controlled laboratory setting.

Additionally, embryo cryopreservation techniques have been substantially improved. Vitrification methods offer enhanced embryo survival, postthaw embryo survival, enabling long-term storage of genetically valuable material.[16] These cryobanked embryos can be used for breeding, conservation, or research across continents, transcending geographical and temporal barriers.[17,18]

Genome editing technologies, such as clustered regularly interspaced short palindromic repeats gene editing (CRISPR)/Cas9 system, are revolutionizing the understanding and manipulation of reproductive traits.[19,20] Precise genetic changes can enhance fertility, disease resistance, heat tolerance, or even alter estrous cycles to better suit production environments.[21-23] For instance, gene-edited males with increased sperm motility or cows resistant to reproductive tract infections could substantially increase productivity and reduce treatment costs in both dairy and beef cattle.[24-29]

Diagnostics and monitoring

Monitoring reproductive health in real-time and with minimal invasiveness is a game-changer for veterinary practitioners.[30,31] Wearable biosensors, similar to fitness trackers in humans, are being developed to monitor vital reproductive parameters such as body temperature, hormonal fluctuations (e.g. progesterone concentrations), locomotion patterns, and even vaginal mucus characteristics (to detect estrus).[29-36] These tools are already successfully used in cattle and horse operations for estrus detection and in companion animals for parturition alerts.

Point-of-care diagnostic devices are becoming increasingly sophisticated, enabling on-site analysis of hormone profiles, semen quality, or uterine health.[37-40] These handheld or mobile-connected devices reduce the need for central laboratory processing and expedite decision-making in the field, especially in rural or resource-limited environments.[41]

A major area of innovation is AI-driven imaging diagnostics. Algorithms trained on thousands of reproductive ultrasonographic images can now assist in identifying ovarian follicular dynamics, early pregnancy, or uterine abnormalities with high accuracy,[42-44] improving diagnostic capabilities of both novice and experienced veterinarians. Furthermore, teleultrasound and teleconsultation platforms enable reproductive evaluations in remote places to be reviewed in real-time by specialists elsewhere, democratizing access to expert care.[45,46]

Collectively, these advancements are moving theriogenology toward predictive and preventative care, enabling early signs of reproductive failure or suboptimal performance to be identified before they adversely impact productivity or health.

Data and precision breeding

Big data analytics are reshaping how breeding decisions are made.[47] Historically, decisions were based on visual appraisal, pedigree and basic performance metrics. Today, precision breeding integrates massive datasets, including genomic profiles, production records, behavioral observations, and environmental factors, to make optimized, individualized reproductive decisions.[48-50]

Machine learning and AI models can analyze complex datasets to forecast estrus onset, calculate ideal breeding times, assess embryo quality,[51-53] and even predict lifetime fertility performance. For instance, AI models trained in dairy herd management software can detect silent heats or flag cows at risk of postpartum reproductive complications.[48,53]

Multiomics approaches, such as transcriptomics (gene expression), proteomics (protein profiles) and metabolomics (metabolite analysis), offers deeper insights into reproductive physiology.[54,55] Elucidating molecular cascades that underlie ovulation, implantation, or embryo development can identify biomarkers for fertility or infertility with unprecedented accuracy.[56-59] Precision reproduction not only increases efficiency but also contributes to sustainability by reducing numbers of animals needed for breeding, decreasing reproductive failures and minimizing reliance on hormonal protocols.[60-62]

Conservation and biodiversity

Theriogenology has a vital and growing role in wildlife conservation and biodiversity preservation. Species extinction rates are rising, driven by habitat loss, climate change and human encroachment.[63] Reproductive technologies are emerging as critical tools in the fight to preserve genetic diversity and rescue species from the brink.[64]

Frozen zoos, biobanks containing cryopreserved sperm, oocytes, embryos, and even somatic cells from endangered animals are expanding. With advances in somatic cell nuclear transfer and induced pluripotent stem cells, it is becoming possible to revive lost genetic lines, or even bring back extinct species, though such applications raise complex ethical questions.[65-68]

Cross-species embryo transfers, where embryos from endangered animals are carried by surrogates of a related, more common species, have been explored in projects involving antelopes, wild cats, and rhinoceroses.[66,69] This method reduces the reproductive burden on the few remaining individuals of an endangered species, thus reducing extinction risk.[70]

Further, the ability to manipulate breeding in captive populations using behavioral and hormonal cues, combined with noninvasive pregnancy monitoring, improves success rates and animal welfare.[71-73] These techniques, coupled with genetic management software, are now integral to zoo breeding programs and species survival plans globally.

One Health and transnational reproductive dynamics

Reproductive health of animals is closely linked with global health through the One Health framework, which recognizes the interconnectedness of human, animal and environmental well-being.[74,75] Some zoonotic diseases, including brucellosis, leptospirosis and toxoplasmosis, often manifest through reproductive pathways, leading to abortion or infertility in animals and posing serious public health risks.[76]

Research in theriogenology helps identify reproductive pathogens, understand transmission dynamics and develop vaccines or mitigation strategies. For instance, improving reproductive biosecurity in livestock can reduce risks of zoonotic outbreaks.[77,78]

Theriogenology also supports translational research, with animal models having key roles in understanding human reproductive disorders such as polycystic ovary syndrome, endometriosis or infertility.[79,80] Transgenic or gene-edited animals offer insights into gene function and pathology, improving treatment strategies across species.[81,82]

Additionally, global research collaborations are increasing. Institutions across continents now share reproductive data, cryopreserved samples and genetic resources under structured regulatory agreements.[83,84] This enhances both domestic animal productivity and global biodiversity initiatives.

Key message

The theriogenology research frontier is rich with transformative possibilities. From AI and gene editing to cross-species reproduction and planetary health, the field is no longer confined to clinical practice, but is truly at a crossroads of biotechnology, conservation and global health. As technology evolves, theriogenologists will have key roles in applying these innovations responsibly, to enhance animal welfare, improve food security and preserve life on earth.

The expanding role of comparative theriogenology

Clinical theriogenology is a vital discipline within veterinary medicine, focused on animal reproduction, encompassing diagnosis, treatment and ART in small and large, domestic and wild/exotic animals. Comparative theriogenology is important, fostering cross-species understanding of reproductive mechanisms that can inform both veterinary and human medicine. In small ruminants (e.g. sheep and goats), laparoscopic artificial insemination is commonly used, enabling precise semen placement into uterine horns, substantially improving conception rates, especially when using frozen semen.[85] In canine reproduction, transcervical artificial insemination has emerged as a minimally invasive alternative to surgical insemination, enabling direct deposition of semen into the uterus without anesthesia, making it ideal for valuable breeding dogs.[86] Equine theriogenology has also had substantial advancements, including hysteroscopic insemination in mares, using an endoscope to visually guide semen deposition near the oviductal papilla, optimizing fertility.[87,88] Beyond insemination techniques, fetal monitoring is critical for assessing fetal health in pregnant animals, e.g. using ultrasonography and hormonal assays to predict complications or developmental issues. In periparturient care, foaling and whelping monitoring programs are being implemented, often involving daily milk calcium testing, body temperature tracking and remote surveillance to anticipate and manage parturition.[89-92] Additionally, advanced procedures such as embryo transfer, IVF and cryopreservation are increasingly integrated into clinical theriogenology, enhancing genetic progress and reproductive efficiency.

Theriogenology in nontraditional and exotic species such as camels, bison, elephants, and various wildlife presents unique challenges and opportunities due to species-specific reproductive anatomy, physiology, and behavior. In camels, both dromedaries and Bactrians, reproduction is influenced by seasonal breeding patterns and induced ovulation, requiring specialized techniques such as transrectal ultrasonography for follicular monitoring and an artificial vagina or electroejaculation for semen collection.[93] Artificial insemination is gaining popularity, although semen preservation remains a challenge. In bison, reproductive management is crucial for both conservation and production. Techniques such as estrus synchronization, artificial insemination and embryo transfer are being adapted from cattle models, with ongoing research aimed at improving success.[94] Elephants, due to their long pregnancy (up to 22 months) and complex social and reproductive behaviors, require intensive reproductive monitoring. Advanced tools such as blood progesterone assays, ultrasonography and endoscopic insemination are employed in both Asian and African elephants, especially in captive breeding programs, to enhance conservation efforts.[95] Additionally, ART are being extended to other species including rhinos, giraffes, and endangered felids, where semen collection, cryopreservation, IVF and intracytoplasmic sperm injection (ICSI) are being researched and applied.[65,96-98] Fetal monitoring, hormone profiling and behavioral observation have critical roles in managing pregnancies in these animals. Theriogenologists working with such diverse species often collaborate with zoological institutions, wildlife reserves, and conservation programs to apply innovative reproductive solutions that support biodiversity, prevent extinction and maintain healthy captive populations. These efforts highlight the expanding scope of clinical theriogenology beyond domestic species, showcasing its importance in wildlife conservation and global ecological sustainability.

The future of theriogenology increasingly depends on integrative, cross-species analyses of reproductive processes, with comparative theriogenologists having pivotal roles as both researchers and facilitators of translational reproductive science. Their importance is evident in 3 key areas: mechanistic understanding, application of reproductive technologies, and conservation-driven ethics. By comparing reproductive physiology and pathophysiology across very diverse species, including birds, mammals, reptiles, and amphibians, these specialists identify conserved and unique biological mechanisms related to hormonal regulation, gametogenesis, and uterine function. This comparative approach enhances diagnostic accuracy and supports development of predictive models to assess effects of environmental stressors-such as elevated temperatures and air pollution-on reproductive health. For instance, human studies have linked extreme heat and air pollutants, including particulate matter and vehicle emissions, to decreased fertility and adverse pregnancy outcomes.[99] Experimental studies in small African mammals under simulated heatwave conditions have similarly demonstrated reduced testosterone concentrations and compromised sperm quality, indicating reproductive vulnerability to climate fluctuations.[100]

In addition to foundational research, comparative theriogenologists have essential translational roles in adapting ART (e.g. cryopreservation, IVF, and embryo transfer) to species with distinct reproductive physiologies. This adaptability is particularly vital for conservation of endangered species, where preservation of germplasm is a critical strategy for safeguarding genetic diversity.[101] Lastly, their involvement in ethically guided biodiversity management is indispensable. They contribute to the design of responsible breeding programs that mitigate inbreeding and support population resilience while evaluating broader ecological and ethical implications of reproductive interventions. Ultimately, advancement of theriogenology will rely not only on technological progress but also on the expertise of professionals who can apply reproductive knowledge across species to address both domestic and global conservation needs.

Teaching: educating the theriogenologists of tomorrow

As theriogenology continues to evolve in research and clinical practice, its teaching must also undergo a paradigm shift.[102] Veterinarians and researchers of tomorrow must be prepared not only to master core reproductive science but also to engage with technologies, ethical frameworks, and global challenges that were previously outside the traditional veterinary curriculum; consequently, theriogenology education will be shaped by innovation in curriculum, teaching methods, interdisciplinary collaboration, and equitable access to resources.[103] The following is a description of how the field is transforming.

Curriculum innovation

Historically, theriogenology education focused heavily on reproductive anatomy, physiology, and clinical procedures related to veterinary obstetrics and gynecology.[104] Although these remain foundational, the curriculum of the future must expand to incorporate cutting-edge scientific disciplines and ethical considerations.[105]

Modules on reproductive genomics and epigenetics are becoming essential, allowing students to understand how genes and gene expression affect fertility, embryo viability, and offspring traits.[51,52] With the advent of CRISPR-based gene editing and genetic engineering, students must also grapple with questions of how and whether these technologies should be applied in clinical or conservation contexts.[106]

Moreover, courses are beginning to emphasize bioinformatics, training students to interpret genomic datasets and apply them to reproductive decision-making. Understanding how to navigate databases, analyze gene expression data, or assess genomic breeding values will be crucial for veterinarians involved in both livestock breeding and research.[107,108]

Another critical area is AI in diagnostics and decision-support systems. Integrating content on how algorithms assist in reproductive imaging, hormone tracking and embryo grading will help students work effectively with emerging tools.[109] Additionally, conservation ethics, population management and One Health perspectives are increasingly woven into theriogenology education to prepare students for complex roles in biodiversity preservation and global health.[110]

Curriculum innovation, particularly through the integration of augmented reality (AR) and related immersive technologies, offers a transformative pathway for veterinary schools to anticipate and adapt to the evolving needs of theriogenology and their learners. AR-based simulations, interactive anatomical models, and virtual clinical scenarios allow students to practice complex reproductive techniques in a controlled, repeatable, and low-risk environment. These tools not only enhance skill acquisition and confidence but also help institutions identify gaps in traditional teaching methods and resource availability. By analyzing student performance data and engagement patterns within these platforms, programs can refine curricula, allocate instructional resources more effectively, and align training with emerging industry competencies. Moreover, embedding digital innovation within teaching fosters institutional agility, enabling schools to respond proactively to technological advances in reproductive medicine. Ultimately, such forward-looking approaches ensure graduates are better prepared to meet the demands of a rapidly advancing specialty.

As there is an 'information explosion' in nearly all aspects of veterinary medicine, there are competing demands amongst numerous disciplines to increase or at least maintain the number of hours to deliver content for that discipline. To ensure that we retain a 'fair share' of instructional time, theriogenologists will need to make a very clear case for the importance of the discipline and of the wide-ranging ramifications of its impact, as described in this review.

Immersive and experiential learning

In a field as hands-on as theriogenology, experiential learning remains essential; however, how students gain that experience is evolving rapidly.[110,111]

Virtual reality (VR) tools[112] now offer highly realistic simulations of procedures like ultrasonography, semen collection, embryo transfer, and dystocia management. These simulations not only allow repetitive practice in a risk-free setting but can also be tailored to represent various species, anatomical anomalies, and clinical complications.

Haptic feedback devices go 1 step further, providing tactile sensations that replicate the feel of transrectal palpation or uterine manipulation.[113,114] This technology can improve student competence and confidence before engaging with live animals, reducing stress for learners and animals.

In addition, AR is also finding applications, particularly in anatomy and physiology teaching. Students wearing AR headsets can observe real-time overlays of reproductive structures on cadavers or models.[115] They can visualize ovulation, embryo migration, or sperm-ovum interactions in 3D, enhancing their spatial understanding of complex processes.

Moreover, telementoring platforms enable students in remote or underfunded areas to connect with experts around the world. Students in sub-Saharan Africa, for example, could observe a live laparoscopic insemination in a European zoo, ask questions in real-time and later review annotated recordings, all through internet-connected devices.[116,117] These platforms not only broaden exposure to rare species and techniques but democratize access to expert instruction.

Remote and hybrid education models

The COVID-19 pandemic accelerated a global shift toward remote learning and many innovations born of necessity are now features of veterinary education.[118] Online modules with embedded assessments, case-based simulations and video demonstrations allow students to engage with material at their own pace and revisit difficult concepts.[119] These resources can be designed to be interactive, prompting students to make clinical decisions and receive instant feedback.

Virtual laboratories, often paired with mailed kits or virtual specimens, facilitate practical skill development, even remotely. For instance, students can practice semen analysis on virtual slides using image analysis software or simulate estrus synchronization protocols using interactive timelines.[114]

Hybrid education models, combining online theory with in-person practicums, offer flexibility and reduce logistical barriers. Institutions are also forming international partnerships to enrich education.[120] For example, veterinary schools in Asia might collaborate with a wildlife reserve in Africa, enabling students to observe reproductive surgeries via livestream or participate in global conservation case studies.

Such models increase exposure to diverse species, breeding systems and ethical contexts, better preparing students for work in a globalized veterinary landscape.

Continued need for live animal teaching use

Although increased utilization of the aforementioned educational innovations is profound in respect to potential educational enhancement, exposure to teaching animals, clinical teaching cases and experiences drawn from experiential learning are also critical. In addition to learning animal handling skills and experiencing adverse animal responses, students develop increased confidence not completely gained from VR and models.

Interdisciplinary integration

Theriogenology has never been a siloed discipline; this is truer now than ever! Today's reproductive professionals must navigate intersections with fields as varied as data science, environmental science, biotechnology, behavioral science, and ethics.[121]

Joint degrees and interdisciplinary capstone projects are becoming more common. For example, a student might study reproductive effects of climate change on migratory wildlife, requiring knowledge of ecology, endocrinology, and conservation policy.[122] Another might assess impacts of selective breeding on canine behavior and welfare, combining genomics, ethology, and ethics.

Curriculum reforms increasingly promote collaboration across departments, allowing students to take electives in bioengineering, AI development, epidemiology, or even law (e.g. regulations regarding animal biotechnology or endangered species protection).[123] Such interdisciplinary education not only expands career opportunities but fosters a systems-thinking approach, essential for solving complex reproductive challenges.

Faculty development and pedagogical evolution

As student expectations and technologies change, faculty development becomes essential. Instructors must be equipped to teach not exclusively content but also tools and methods of modern education.[124,125]

Workshops and certifications in digital pedagogy, VR and AR facilitation, flipped classrooms, and problem-based learning (PBL) are now common in progressive veterinary training programs. In PBL settings, students tackle real-world reproductive cases, developing critical thinking, and clinical reasoning skills under guided mentorship.[126,127]

Educators are also learning to incorporate formative assessment tools, such as online quizzes, interactive polls and discussion forums to provide continuous feedback and foster student engagement.[128,129] Lecture-based teaching is being replaced by active learning environments that better prepare students.

Global equity in education

As theriogenology education advances, it is vital that these innovations do not remain confined to wealthy institutions.

Open-access platforms offering massive open online courses, multilingual content and low-bandwidth resources can help students in developing countries access world-class education.[130] For example, recorded lectures with subtitles in Swahili or Hindi can substantially broaden reach.

Donor-funded initiatives and public-private partnerships could provide institutions in under-resourced regions with access to simulation tools, teaching materials, and faculty training. International veterinary associations can facilitate resource-sharing, cross-border teaching exchanges, and joint certification programs to promote standardized, high-quality education globally,[131] all of which facilitate equitable access.

Furthermore, efforts to contextualize content, e.g. including local species, cultural practices and region-specific reproductive challenges, ensure that global education is also locally relevant.[132] Equity in theriogenology education not only supports development of competent local practitioners but also strengthens global conservation efforts and animal health outcomes.[133]

Addressing global equity in education and resource disparity requires not only promoting open access but also acknowledging the substantial costs associated with developing and disseminating advanced theriogenology technologies. Sustainable funding will likely rely on a blended model that includes public–private partnerships, targeted governmental and philanthropic grants, and strategic collaborations with industry to support early-stage research and development. Open-access dissemination can be subsidized through institutional support, cost-sharing frameworks, and integration of tiered or deferred-cost models for low-resource regions. Additionally, investing in scalable digital platforms, shared international training hubs, and open-source tools can reduce long-term distribution costs. Recovery of development expenses may be achieved indirectly through improved efficiency in clinical and production systems, licensing of specialized applications, and reinvestment of revenue generated from premium services in high-income settings. Collectively, these approaches ensure that innovative reproductive technologies become broadly accessible while maintaining the financial viability necessary for continued advancement.

Key message

Theriogenologists' future education is undergoing profound transformation. Modern curricula are integrating advanced science, immersive technologies, interdisciplinary collaboration, and global perspectives. Educators are adopting active, inclusive, and tech-enabled approaches, whereas institutions are forging partnerships to deliver hybrid, flexible learning.

At the heart of this evolution is a simple but powerful idea: tomorrow's reproductive specialists must be not only clinically competent but also ethically grounded, technologically fluent, globally aware, and equipped to drive innovation. Preparing such professionals requires rethinking how, what and for whom we teach theriogenology and ensuring that no aspiring veterinarian, irrespective of geography or background, is left behind.

Role of theriogenology in future outreach

As theriogenology continues to evolve through scientific and technological advancement, its role in outreach will become increasingly important in bridging the gap between laboratory discoveries and real-world applications. Outreach in this context goes well beyond public education; it encompasses community engagement, producer education, wildlife conservation, global health collaboration, and democratization of ARTs. In the future, theriogenologists will have pivotal roles not only in advancing science but also in leading meaningful changes at grassroots levels.[131,134,135]

One of the most impactful areas for future outreach is livestock and rural veterinary services. In many parts of the world, especially in low- and middle-income countries, reproductive inefficiency remains a major barrier to food security and economic development. However, through extension programs, theriogenologists can bring improved breeding techniques, fertility management tools and disease prevention strategies directly to owners and herders. Mobile veterinary clinics, AI-powered reproductive health monitoring apps and hands-on training sessions can empower communities to improve herd productivity and reduce reproductive losses. This not only enhances livelihoods but also promotes animal welfare and sustainable agriculture.[136,137]

Theriogenology will also serve as a key outreach tool in wildlife conservation and biodiversity protection.[138] As climate change, habitat loss and poaching continue to threaten species, reproductive specialists will be instrumental in developing and delivering conservation programs.[139,140] Outreach initiatives may include collaboration with national parks, zoos, and indigenous communities to support population management, genetic preservation and ARTs in endangered species.[141-143] Educational campaigns can raise public awareness about the importance of reproductive technologies in preventing extinction and maintaining ecological balance.

Another growing frontier for theriogenology outreach lies in One Health and zoonotic disease prevention. Because many reproductive diseases in animals have implications for human health, outreach programs can help detect, monitor, and control diseases that impact both sectors.[131,144] Theriogenologists, working alongside public health officials, can help educate rural and urban communities on appropriate breeding practices, reproductive hygiene, and disease transmission pathways.[135] Under zoonotic disease prevention, especially rabies, we must address the severe public health threat posed by stray dogs in developing countries, where rabies causes ~ 59,000 deaths annually.[145] Theriogenologists can have a critical role in mitigating this crisis by advancing nonsurgical sterilization methods (e.g. chemical or hormonal alternatives) to support large-scale, humane control of animal populations.[146] This integrated approach enhances preparedness and resilience in the face of emerging health threats.

Educational outreach will also take on new dimensions. Through online platforms, social media and interactive learning modules, theriogenologists can readily share their knowledge with veterinary students, animal owners, conservationists, and the general public.[147-150] Future outreach will include webinars on emerging technologies (e.g. nonsurgical contraception[146]), virtual demonstrations of reproductive procedures, and open-access resources in multiple languages.[151,152] These tools will be particularly important in reaching under-resourced or geographically isolated regions, ensuring equitable access to reproductive knowledge and services.[153]

Finally, theriogenology can have a critical role in policy advocacy and public dialogue. As debates surrounding gene editing, reproductive ethics, and animal welfare intensify, reproductive specialists should be involved as informed voices to shape responsible policy.[154,155] Outreach will include participation in public forums, stakeholder meetings and collaborations with NGOs and regulatory bodies to promote ethical, science-based practices.

Key message

Theriogenology future is not confined to research laboratories or clinics; in contrast, it extends into farms, forests, classrooms, and communities. By embracing outreach as a core function, theriogenologists will become powerful agents of change, advancing reproductive health, animal welfare, and public understanding in a complex and interconnected world.

Challenges and ethical landscape

Despite promising advancements in reproductive science and education, the future of theriogenology is not without substantial challenges, many of which lie in ethical, social and infrastructural domains. One of the most pressing concerns revolves around bioethics.[156,157] The increasing use of genome editing technologies (e.g. CRISPR/Cas9) raises complex questions. For example, is it ethically justifiable to alter an animal's genetic code for enhanced productivity or aesthetic traits? Although these tools have enormous potential to eliminate hereditary diseases and improve fertility, they also risk unintended genetic consequences and may compromise animal welfare if misused or poorly regulated.[154,155,158]

In wildlife and conservation contexts, ART may conflict with natural behaviors and ecological balance.[65,159] Overreliance on artificial breeding and gene manipulation could undermine natural selection processes, reduce genetic diversity, or interfere with species adaptation.[160,161]

Resource disparity is another major concern. Many cutting-edge tools (e.g. AI-based diagnostic platforms, VR training systems, genomic sequencing) are expensive and often limited to elite academic or research institutions. This creates an uneven playing field, where rural veterinary schools or institutions in low- and middle-income countries may struggle to access or implement these innovations, widening gaps in global education and research. However, as noted above, donor-funded initiatives and public-private partnerships are potential sources of support.

Additionally, regulatory fragmentation across countries complicates application of ARTs. Differing standards on gene editing, animal welfare, data privacy, and cross-border biological sample sharing can delay or obstruct collaborative research.[162]

In considering the future of theriogenology, it is essential to acknowledge the potential for unethical use of emerging reproductive technologies outside the boundaries of jurisdictional veterinary practice act regulations or without a valid veterinary–client–patient relationship (VCPR). As tools become more accessible, the risk increases that individuals lacking appropriate training or legal authority may attempt to implement them, potentially compromising animal welfare, biosecurity, and data integrity. To mitigate these risks, clear regulatory frameworks, robust professional oversight, and internationally harmonized guidelines are needed to define who may access and apply such technologies. Education of stakeholders, including producers, breeders, and paraprofessionals, will also be crucial in reinforcing the ethical and legal obligations associated with their use. Additionally, technology developers should incorporate safeguards such as traceability, user authentication, and decision-support systems that flag inappropriate applications. Proactive governance will be fundamental to ensuring that innovation enhances, rather than undermines ethical veterinary practice. The practice of veterinary medicine, including theriogenology, is generally regulated by state/provincial or national veterinary licensing bodies. Given the great potential of current and emerging technologies to increase productivity and/or profitability, there will need for critical oversight by regulatory bodies to mitigate unethical use of these technologies outside of jurisdictional veterinary practice act regulations and/or valid veterinary client patient relationships.

Lastly, the pace of technological change demands substantial capacity-building. Not all educators or students are immediately equipped to adopt new tools or methodologies. Ensuring equitable access, proper training and ongoing support will be critical to avoid excluding those without prior exposure to digital or genetic technologies.[163]

Authors' reflections on a discipline in motion

The future of theriogenology in veterinary education will be shaped by the growing need to integrate reproductive medicine more deeply and effectively into core veterinary curricula. As advancements in reproductive technologies become increasingly central to animal production, conservation and companion animal care, veterinary schools must enhance student exposure to theriogenology through simulation-based training, hands-on experiences, and interdisciplinary coursework. Early clinical integration of contemporary tools, such as ultrasonography, minimally invasive surgical techniques, artificial insemination, embryo transfer, and population control strategies, along with One Health perspectives, can spark student interest and build foundational competencies. Furthermore, promoting elective rotations, externships, and mentorship opportunities in theriogenology will help address the current shortage of specialists and inspire more students to pursue this vital discipline. By modernizing and prioritizing reproductive education, veterinary programs can ensure that graduates are better equipped to support animal health and industry needs in both clinical and research settings.

At the postgraduate level, theriogenology residency training programs must adapt to the rapidly evolving landscape of veterinary medicine by embracing ARTs, fostering interdisciplinary collaboration and increasing emphasis on both clinical and research specialization. As demand for reproductive expertise grows across companion animals, livestock and exotic species, residency programs should integrate cutting-edge practices such as embryo transfer, cryopreservation, reproductive genomics, and minimally invasive procedures. Expanding access to training through virtual platforms, international partnerships and structured mentorship can help overcome limited numbers of residency positions. By modernizing curricula and fostering innovation, residency programs can prepare future theriogenologists to meet complex reproductive challenges across species, including zoo, wild and endangered animals, while also contributing to global food security, biodiversity conservation, and animal welfare.

Another important consideration when envisioning the future of comparative theriogenology is continued diversification into a wide range of specialized domains, reflecting the complexity and interdisciplinary nature of reproductive science. Emerging areas such as reproductive epidemiology, reproductive immunology, and reproductive pathology are at the forefront of this transformation, offering critical insights into fertility management, disease prevention, and reproductive efficiency across species. Fields like reproductive biotechnology, molecular reproductive biology, and cryobiology are also gaining momentum, driving innovation in ARTs, genetic preservation and genome editing. Comparative theriogenology, in particular, is a valuable framework for understanding species-specific reproductive mechanisms, and for translating findings between veterinary and human medicine. Moreover, advances in reproductive endocrinology continue to improve hormonal diagnostics and treatments, while environmental reproductive toxicology is addressing impacts of pollutants, endocrine disruptors, and climate change on reproductive outcomes. Collectively, these specialized domains are reshaping theriogenology into a more highly integrated, data-driven, and preventive discipline, better equipped to support sustainable reproductive management and overall animal health, in the face of global challenges.

Despite these advancements, the future of theriogenology also faces many challenges, particularly in rural and large animal practice settings. As reproductive efficiency becomes increasingly critical to profitability of livestock operations, theriogenologists will assuredly have pivotal roles in advancing herd health and productivity in agricultural communities. However, workforce shortages and limited access to specialized reproductive services threaten the sustainability of theriogenology in these areas. In corporate practice models, theriogenology is gaining recognition for its ability to improve reproductive performance metrics, though its integration often prioritizes standardized protocols over individualized care. Additionally, ongoing pay disparities between theriogenologists and those in more lucrative specialties (e.g. small animal medicine, surgery and diagnostic imaging) raise concerns about long-term retention and career satisfaction. These financial disparities may also deter talented graduates from pursuing residency training in theriogenology, further exacerbating the shortage of specialists. Addressing compensation gaps, increasing visibility of the field's impact and reinforcing the value of reproductive expertise across all sectors will be essential to ensuring theriogenology has continued vitality and growth.

Conclusion

Looking ahead, theriogenology stands on the brink of a transformative era, driven by rapid advances in science and technology. In research, powerful tools (e.g. gene editing, AI, multiomics, reproductive conservation techniques) will redefine how we approach fertility, animal health, and species preservation. Simultaneously, education in theriogenology is evolving through immersive simulations, hybrid learning environments, and interdisciplinary integration, equipping future professionals with technical skills, ethical frameworks, and global outlook. However, realizing this potential requires collective action to address pressing challenges, ranging from bioethics and regulatory complexity to disparities in access and training. Therefore, the next generation of theriogenologists must be not only clinically proficient but also visionary stewards of innovation, working to advance animal welfare, biodiversity, and sustainable veterinary practice.

Conflict of interest

None to declare.

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