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GENOMIC PRECISION IN ANIMAL REPRODUCTION: A PATHWAY TO ENHANCED BREEDING PROGRAMS

PRECIZIA GENOMICĂ ÎN REPRODUCȚIA ANIMALELOR: O CALE PENTRU ÎMBUNĂTĂȚIREA PROGRAMELOR DE AMELIORARE

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ABSTRACT | **REZUMAT**

This review delves into the intricate synergy between genomic selection and sexed semen technology within the context of animal breeding programs. It scrutinises the underlying principles and methodologies of genomic selection and traces its evolutionary trajectory in the realm of animal breeding. Furthermore, it comprehensively elucidates the technological underpinnings of employing sexed semen in animal reproduction, offering concrete illustrations of its manifold applications. Additionally, the review elucidates the rationale substantiating the amalgamation of genomic selection and sexed semen technology, expounding on how genomic insights augment the precision of sexed semen sorting and the refinement of trait selection. It scrutinises the collaborative strategy's potential for optimising genetic advancements within breeding programs. Nonetheless, the review meticulously elucidates the multifaceted challenges and ethical quandaries entailed in deploying this technology, underscoring the imperative for future research endeavours to address these complexities and persist in refining this integrated approach. In summation, this review underscores the pivotal role of genomic precision in the domain of animal reproduction, simultaneously offering insights into potential avenues for further advancement in this field.

Keywords: sexed semen, genomic selection, genetic gain

Această lucrare analizează sinergia complexă dintre selecția genomică și tehnologia materialului seminal sexat în contextul programelor de ameliorare a animalelor. Aceasta analizează principiile și metodologiile care stau la baza selecției genomice și urmărește traiectoria evolutivă a acesteia în domeniul creșterii animalelor. În plus, elucidează în mod cuprinzător fundamentele tehnologice ale utilizării materialului seminal sexat în reproducerea animalelor, oferind ilustrații concrete ale multiplelor sale aplicații. Totodată, lucrarea elucidează în mod sistematic raționamentul care justifică amalgamarea selecției genomice și a tehnologiei materialului seminal sexat, explicând modul în care cunoștințele genomice sporesc precizia sortării materialului seminal sexat și perfecționarea selecției trăsăturilor. În plus, analizează potențialul strategiei de colaborare în optimizarea progreselor genetice în cadrul programelor de selecție. Totodată, sunt prezentate provocările și dilemele etice pe care le implică implementarea acestei tehnologii, subliniind imperativul ca viitoarele eforturi de cercetare să abordeze aceste complexități și să persiste în perfecționarea acestei abordări integrate. În concluzie, această lucrare subliniază rolul esențial al preciziei genomice în domeniul reproducerii animalelor, oferind în același timp perspective asupra unor potențiale căi de avansare în acest domeniu.

Cuvinte cheie: material seminal sexat, selecție genomică, câștig genetic

Genomic precision plays a pivotal role in enhancing animal reproduction and, in turn, improving breeding programs. This precision is realized through two essential components: genomic selection, which leverages genomic information for informed breeding decisions, and the integration of sexed semen, a technology enabling the targeted selection of offspring sex (1, 9, 5). Genomic selection has heralded a paradigm shift in breeding programmes by providing more precise and dependable insights into an animal's genetic potential. By scrutinising an animal's DNA, genomic selection facilitates the identification of desirable traits and significantly enhances the accuracy of predicting an animal's breeding value (2, 9). This newfound precision empowers breeders to make astute choices when selecting animals for breeding, thereby accelerating genetic progress and elevating overall herd performance (2, 9, 13, 5).

Simultaneously, the incorporation of sexed semen into breeding programmes augments the precision

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and efficiency of animal reproduction. This technology provides breeders with the ability to selectively produce the desired sex of offspring, carrying substantial economic and managerial advantages (2, 9, 5, 13). For instance, in dairy herds, the application of sexed semen can elevate the proportion of valuable heifer calves—integral for herd replacement—while curbing the number of less sought-after bull calves (2, 13). This not only enhances the overall genetic calibre of the herd but also augments the profitability of the breeding programme (2, 13, 15).

Furthermore, the fusion of genomic selection and sexed semen technology unveils unparalleled potential for advancing breeding programs. Genomic selection furnishes vital insights into an animal's genetic potential, while sexed semen technology offers the capability to select the desired sex of offspring (5, 9, 13). By harnessing these technologies in unison, breeders can optimise genetic advancement within their herds, selecting the finest animals for breeding and ensuring the production of the desired sex of progeny (5, 9, 13).

In summation, the import of genomic precision in animal reproduction resides in its capacity to refine breeding programs. This is accomplished by providing more accurate insights into an animal's genetic potential and by allowing for the selective production of desired offspring sexes. The integration of genomic selection and sexed semen technology empowers breeders to expedite genetic progress, enhance herd performance, and amplify profitability (2, 5, 9, 13, 15). This review aims to comprehensively examine the intersection of genomic precision, specifically genomic selection, and sexed semen technology in the realm of animal reproduction and breeding programmes.

GENOMIC SELECTION IN ANIMAL BREEDING

Genomic selection represents a transformative breeding technique that leverages genomic information to make precise predictions regarding an individual's breeding value for a specific trait. Its advent has ushered in a revolution in animal breeding, delivering predictions that are markedly superior in accuracy and reliability compared to traditional methodologies (6, 10).

The origins of genomic selection can be traced back to the early 2000s, coinciding with pivotal advancements in genotyping technologies that enabled cost-effective profiling of vast arrays of genetic markers distributed across the genome (11). This technological leap revealed the potential for these markers to furnish more accurate predictions of an individual's genetic potential than relying solely on pedigree information (11). While its conceptualization initially found roots in plant breeding, genomic selection rapidly found adaptation and integration into the realm of animal breeding (10).

Presently, genomic selection has attained widespread acceptance and implementation across various livestock species, underscoring its contemporary significance in animal breeding. The methodology entails genotyping individuals for thousands of genetic markers and subsequently utilising statistical models to estimate their breeding values based on the marker data (6, 10). These estimated breeding values, derived from genomic data, serve as the foundation for pivotal selection decisions, including the identification of animals for breeding or the retention of specific offspring (6, 10).

An undeniable advantage of genomic selection is its capacity to deliver highly accurate predictions of an individual's genetic potential at a remarkably early stage, even before they have the opportunity to produce any progeny (6, 10). This prescient capability empowers breeders to make informed decisions concerning the selection of breeding candidates, consequently accelerating genetic progress and enhancing overall herd performance (6, 10). Moreover, genomic selection facilitates the identification and prioritization of individuals exhibiting desirable traits that may be challenging to measure or observe directly, such as disease resistance or feed efficiency (10).

Nevertheless, genomic selection is not without its constraints. One such limitation revolves around the necessity for a substantial reference population equipped with both genotypic and phenotypic data, serving as the foundation for the development of accurate prediction models (10). The availability of such reference populations may be limited, especially in the case of rare or recently established breeds (11). Another pertinent limitation pertains to the potential for overfitting, a scenario wherein prediction models perform exceptionally well on the training dataset but falter when applied to new individuals (10). This underscores the paramount importance of rigorous validation and independent testing of prediction models to ensure their reliability and generalizability.

ADVANCEMENTS IN SEXED SEMEN TECHNOLOGY: PRINCIPLES AND APPLICATIONS

Sexed semen technology represents a remarkable advancement in reproductive techniques, offering the precision to selectively produce offspring of the desired sex. At its core, this technology exploits the inherent dissimilarities in DNA content between X and Y sperm cells, thereby enabling the sorting and collection of sperm cells based on their sex (8, 14).

Several methodologies are employed to separate X and Y sperm cells within sexed semen technology.

Among these, flow cytometry stands out as a prominent approach. In this method, sperm cells are treated with a fluorescent dye that binds to DNA and are then subjected to a flow cytometer. The flow cytometer detects the fluorescence emitted by stained sperm cells, effectively sorting them into separate collection tubes based on their DNA content (8, 14).

Sexed semen technology has found multifarious applications within animal reproduction. In dairy cattle breeding, it is frequently employed to augment the proportion of female calves, which hold greater value for herd replacement purposes. This strategic use allows dairy farmers to selectively breed their highest-performing cows, thereby enhancing the genetic quality of their herd (14, 15). In beef cattle breeding, sexed semen serves diverse purposes, including the production of more heifer calves for replacement or the alignment with specific market preferences for one sex over the other (21).

The utilisation of sexed semen technology brings forth several potential benefits. Firstly, it bestows breeders with the power to choose the sex of the offspring, a capability that carries economic and management advantages. For instance, in dairy herds, the application of sexed semen can amplify the number of heifer calves—highly prized for their replacement potential—while diminishing the count of less desirable bull calves (14, 15). Secondly, this technology enhances the efficiency of breeding programmes by enabling breeders to concentrate their resources on breeding animals of the preferred sex, thus optimising genetic progress (21). Lastly, sexed semen technology holds the potential to aid in the preservation and propagation of rare or endangered breeds by facilitating the selective breeding of the desired sex (21).

However, the deployment of sexed semen is not without its challenges. A major hurdle lies in its reduced conception rate when compared to conventional semen. The sorting process can negatively impact sperm cell viability, resulting in lower fertility (8, 14). This reduction in fertility may lead to decreased pregnancy rates and additional costs associated with repeated inseminations. Furthermore, the effectiveness of sexed semen technology can vary across different species and breeds, with some proving more amenable to the technique than others (20, 21).

INTEGRATION OF GENOMIC SELECTION AND SEXED SEMEN

The seamless integration of genomic selection and sexed semen technology represents a pivotal advancement in the arena of animal reproduction. This fusion yields a multitude of advantages, including the amplification of genetic progress and the precise realisation of breeding objectives. In this regard, a study by Walsh et al. (2021) delved into the economic impact of using sexed semen and genomic testing in a pasture-based dairy production system (23). The results revealed a higher net benefit when sexed semen and genomic testing were combined, compared to the solitary utilisation of genomic testing. This judicious amalgamation offered a commendable return on investment within a decadal purview across diverse farming systems (22). Ettema et al. (2017) explored the economic opportunities of deploying sexed semen and semen from beef bulls in dairy herds. Their investigation illuminated the economic allure of using sexed semen on genetically elite specimens, particularly in younger generations, resulting in an amplified genetic landscape within the herd. When complemented with genomic testing, the use of sexed semen emerged as an even more potent catalyst, expediting genetic progress (4). Additionally, in a comprehensive review, Moore and Hasler (2017) discussed the potential of incorporating sexed semen, genomic selection, genome editing, and gene drives into juvenile *in vitro* embryo production and embryo transfer programs. They delineated the prospects of curtailing the generation interval and elevating the fidelity of genetic selection by orchestrating the synergistic interplay of these pioneering technologies (12). This convergence has the potential to redefine the horizons of genetic enhancement in animal reproduction. On the other hand, Pedersen et al. (2011) undertook a comprehensive comparative assessment of diverse genomic selection strategies within dairy cattle breeding programs, with a specific focus on the deployment of sexed semen. Their discerning study unravelled nuanced dynamics, revealing that the utilization of sexed semen, in conjunction with multiple ovulation and embryo transfer (MOET), exerted minimal influence on the genetic trajectory of the entire population. However, when coupled with marker-assisted selection, the deployment of sexed semen exhibited more discernible ramifications, further accentuating its significance (16).

These illustrative instances underscore the incontrovertible success engendered by the seamless integration of genomic selection and sexed semen technology within animal reproduction paradigms. The symbiosis of these methodologies ushers in the prospect of augmented genetic advancement, curtailed generation intervals, and the optimisation of breeding programme efficiency. By leveraging genomic insights to judiciously select genetically superior specimens and wielding sexed semen to preside over the offspring's gender, breeders can deftly navigate the path towards precision in realising specific breeding objectives.

It is incumbent to acknowledge that the harmonious amalgamation of genomic selection and sexed semen technology necessitates the dexterous navigation of challenges and considerations. These encompass ethical quandaries, regulatory imperatives, public sentiment, and the contours of economic and logistical feasibility. Nonetheless, with sagacious implementation and adept stewardship, the fusion of these technologies bequeaths an invaluable contribution to the amelioration of animal breeding programs, charting a course towards a future marked by precision and efficacy.

MAXIMISING GENETIC GAIN WITH GENOMIC PRECISION

Genomic precision stands as an indispensable tool in the pursuit of specific breeding objectives by offering unparalleled accuracy and reliability about an organism's genetic makeup. It involves the use of genomic technologies, including genotyping and sequencing, to identify and scrutinise precise genes or markers intricately linked to desired traits. This information can then be used to make informed breeding decisions and select individuals with the highest genetic potential for desired traits.

One of the preeminent applications of genomic precision in breeding is genomic selection. This technique deploys genomic information to gauge the breeding value of individuals, leveraging genetic markers for this estimation (Goddard, 2008). By integrating genomic data into traditional breeding programs, breeders can unearth and select individuals with exceptional genetic merit for specific traits at an early stage, even before these traits manifest phenotypically. This strategic approach fosters not only pinpoint-precision in selection but also swift genetic advancement, ultimately culminating in the realisation of precise breeding objectives (6, 18).

Another pivotal facet is precision breeding, which leans on the utilization of functional markers (FMs) intricately linked to specific genes or genomic regions associated with desired traits (17). FMs offer a granular understanding of the presence or absence of specific alleles or variants that exert influence over trait expression. By homing in on these highly specific markers, breeders can calibrate their breeding decisions with exceptional precision, elevating the efficiency and efficacy of their breeding programmes (17).

This combined approach, wielding the power of genomic precision in breeding programmes, invariably catalyses the augmentation of genetic gain. By embracing genomic information, breeders can meticulously pinpoint individuals with superlative genetic potential for desired traits, even at a nascent developmental stage. This precision, in turn, facilitates an expedited selection process, propelling genetic progress and the actualization of well-defined breeding objectives. The incorporation of genomic precision also empowers breeders to make decisions that are not only informed but also astutely targeted, further augmenting the efficiency and effectiveness of their breeding programmes (18, 19).

Statistical analyses and simulations have played an instrumental role in substantiating the profound impact of genomic precision on breeding programs. These rigorous examinations often juxtapose the genetic gains achieved through traditional breeding methods with those attained through the incorporation of genomic information. The results resoundingly demonstrate that the utilization of genomic information begets higher genetic gains, fosters a more rapid selection response, and refines the precision of breeding value predictions (1, 3, 7). For instance, consider a study that scrutinised within-breed and multibreed genome-wide association studies (GWAS) employing whole-genome sequence data for dairy cattle breeds. The findings showcased that multi-breed GWAS exhibited greater power and precision in identifying genomic regions linked to production traits, underscoring the promise of employing genomic information from diverse breeds to elevate breeding programs (1).

CHALLENGES AND CONSIDERATIONS

The implementation of genomic precision and sexed semen technology in animal reproduction presents a multifaceted landscape rife with intricate challenges and potential bottlenecks, each demanding meticulous consideration from a scientific, ethical, and practical standpoint.

Ethical considerations loom large on the horizon, stemming from the profound implications of manipulating an animal's genetic makeup and employing reproductive technologies. Central to these concerns are apprehensions regarding animal welfare, the spectre of unintended consequences, and the profound moral implications inherent in the act of altering genetic traits. Navigating this ethical quagmire necessitates the establishment of robust ethical frameworks capable of guiding the responsible and ethically sound utilisation of these transformative technologies.

Regulatory dimensions further complicate the path towards implementation. Rigorous regulatory requirements, which may encompass specific genomic technologies or genetically modified organisms, introduce a labyrinthine layer of complexity. Ensuring compliance with these regulations can prove to be a time-consuming and financially taxing endeavour, potentially acting as a significant impediment to the widespread adoption of genomic precision and sexed semen technology in the realm of animal reproduction.

Public perceptions and acceptance form yet another tier of challenges. Misgivings regarding safety, environmental ramifications, and the ethical dimensions of genetic manipulation and sex selection can cast a shadow of scepticism over these technologies. To counteract these concerns and establish trust in technology, comprehensive public education, and engagement initiatives become imperative.

Economic and logistical constraints assume a palpable presence as substantial hurdles. The financial costs associated with genomic technologies, such as genotyping and sequencing, may emerge as insurmountable barriers for certain breeders or producers. Moreover, the requisite infrastructure and expertise required for proficient genomic analysis and interpretation may not be uniformly accessible across diverse settings. The dearth of high-quality reference populations, databases, and reproductive technologies compounds the challenges, especially for specific animal populations or breeds.

Furthermore, the integration of genomic precision and sexed semen technology into existing breeding programmes mandates a substantial overhaul of management practices and data collection protocols. This logistical transformation can pose formidable challenges, particularly within large-scale or heterogeneous breeding programs. Streamlining the coordination of data collection, analysis, and decision-making processes is imperative to ensure the efficient implementation of these technologies.

To address these multifaceted challenges, a concerted effort is required. The establishment of comprehensive ethical frameworks, diligent adherence to regulatory mandates, active public engagement, strategic investments in infrastructure and expertise, and the development of cost-effective solutions are all crucial components of this endeavour. Collaboration across an array of stakeholders, including researchers, breeders, regulatory authorities, and the public, emerges as the linchpin for surmounting these challenges and achieving the successful integration of genomic precision and sexed semen technology in the field of animal reproduction. In this collaborative spirit, we can aspire to harness the full potential of these technologies, fostering progress, sustainability, and efficiency in animal agriculture and conservation.

CONCLUSIONS

The synergy between these two facets of modern breeding programmes emerges as a potent force, holding the potential to revolutionise the field of animal reproduction and breeding. Genomic precision, harnessed through advanced genotyping and sequencing technologies, stands as a beacon of progress in animal breeding. It empowers breeders with the unparalleled ability to decipher an individual's genetic potential for specific traits with remarkable accuracy and foresight. This transformative capability allows for informed breeding decisions, even before phenotypic traits manifest, leading to swift genetic progress and the attainment of specific breeding objectives.

Sexed semen technology, an ingenious reproductive technique, enables the selective production of offspring of the desired sex, aligning breeding programmes with economic and management goals. This technology, when integrated into breeding programmes, offers a pathway to optimise the sex ratio of offspring, ensuring that breeding objectives are met with precision. In dairy herds, for instance, the use of sexed semen has the potential to yield more heifer calves for replacement purposes while curbing the production of unwanted bull calves.

The fusion of genomic precision and sexed semen technology represents a holistic approach to breeding programmes, one that harnesses genetic knowledge to steer reproductive outcomes. By using genomic data to inform breeding decisions and sexed semen to manifest those decisions with precision, breeders can accelerate genetic advancement while ensuring the production of the desired sex of offspring. This dual strategy epitomises the optimisation of resources and the maximisation of genetic progress.

Nonetheless, the journey towards implementing these advanced technologies is not devoid of challenges. Ethical considerations underscore the need for responsible and ethical use, while regulatory complexities, public perceptions, and economic/logistical constraints pose formidable hurdles. The establishment of ethical frameworks, regulatory adherence, public engagement, and resource allocation becomes imperative to navigate these challenges effectively.

In the quest for genomic precision, genomic selection and precision breeding emerge as pivotal tools, elucidating an animal's genetic landscape and guiding selective breeding. In tandem with sexed semen technology, these tools offer breeders the promise of enhanced breeding efficiency, accelerated genetic progress, and the ability to achieve specific breeding objectives.

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