BIOTECHNOLOGY IN POULTRY GENETICS: PATHWAYS TO DISEASE RESISTANCE AND ENHANCED GROWTH EFFICIENCY

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REVIEW

Abstract
This mini review explores the transformative impact of biotechnological advancements in poultry genetics, focusing on the integration of gene editing technologies and artificial intelligence (AI) into the field. Recent developments in gene editing, particularly the precision offered by tools such as CRISPR/Cas9, have unlocked new possibilities for enhancing disease resistance and growth efficiency in poultry breeds. These technological advancements enable targeted modifications within the poultry genome, leading to the development of breeds with improved health, productivity, and sustainability. Concurrently, the application of AI in genetic selection processes has begun to revolutionize breeding programs. By analyzing extensive genomic data, AI algorithms can identify genetic markers linked to desirable traits, facilitating a more efficient and precise selection of superior breeding candidates. This review delves into the potential of combining gene editing and AI to accelerate genetic advancements in poultry, creating breeds tailored to meet specific production needs and market demands. Ethical and regulatory considerations surrounding these biotechnological interventions are discussed, emphasizing the need for responsible use to ensure animal welfare, environmental sustainability, and consumer safety. The integration of these technologies promises not only to advance poultry genetics but also to address global food security challenges, contingent upon navigating ethical, regulatory, and societal hurdles.

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INTRODUCTION

Poultry farming stands as a cornerstone of global food security, significantly contributing to the dietary needs of humans through the provision of proteins, calories, and essential micronutrients (Govoni et al., 2022, Șonea et al., 2023, Szakacs et al., 2015, Avarvarei et al., 2019). The strategy of livestock diversification, which encompasses poultry farming, plays a crucial role in fortifying household food security. It achieves this by mitigating the impacts of infectious diseases and fostering the economic resilience of rural communities (Terfa et al., 2015). In many developing nations, village poultry notably aids in poverty alleviation and bolsters household food security, marking a critical element in the socio-economic fabric (Alders & Pym, 2009).

However, the poultry industry is besieged by various challenges that jeopardize food security (Colibar et al., 2013, Colibar et al., 2020, Gheorghe-Irimia et al., 2023). Outbreaks of highly pathogenic avian influenza, exemplified by the H5N1 strain, represent a significant threat to both public health and the poultry sector, underscoring the urgency for robust disease control strategies (Makalo et al., 2022). Concurrently, the menace of antimicrobial resistance within poultry farming has emerged as a global concern, with implications for food security, economic stability, and gender equity. The prevalence of multidrug-resistant pathogens, such as certain strains of Salmonella linked to poultry, poses a grave threat to public health and food safety (Hedman et al., 2020; Manoj, 2015).

Exacerbating these challenges, external factors like climate change and global warming adversely affect the availability and quality of animal feed, thus impacting production costs and, subsequently, food security (El-Hack et al., 2020). The COVID-19 pandemic further strained the poultry industry, accentuating the imperative for resilience and adaptability to maintain food security (Selim, 2021; Bamidele & Amole, 2021). Addressing these obstacles necessitates enhancing the decision-making capabilities of poultry farmers, encouraging the adoption of innovative technologies, and fostering self-sufficiency in poultry meat production (Tumwebaze et al., 2018; Khan et al., 2022; Alnafissa et al., 2021). Properly managed backyard poultry farming, with stringent biosecurity measures, significantly contributes to poverty alleviation and food security in rural locales (Fagrach et al., 2023; Conan et al., 2012).

Amidst these multifaceted challenges, biotechnology emerges as a vital ally in the poultry industry, offering groundbreaking solutions that span from disease management to the enhancement of production efficiency. Biotechnological interventions in poultry breeding have led to notable improvements in growth, egg production, and disease resistance through genetic manipulation (Abdelaziz, 2024). These advancements facilitate the rapid identification of pathogens using DNA-based techniques and the creation of biological products, including vaccines, to bolster the immune response against various diseases (Abdelaziz, 2024).

Moreover, biotechnology has played a pivotal role in enhancing feed utilization through the introduction of both natural and synthetic additives, thereby optimizing the nutritional value of poultry diets, and maximizing production efficiency (Abdelaziz, 2024). Innovations such as marker-assisted selection, gene knockdown technologies, and CRISPR/Cas-mediated gene editing have accelerated genetic improvements in poultry, leading to superior performance traits (Bhattacharya et al., 2022).

Additionally, the application of biotechnology extends to the production of recombinant proteins and vaccines, utilizing avian embryos and cell lines as biomanufacturing platforms. These efforts not only improve production efficiency but also pave the way for developing novel byproducts from poultry processing (Shamsuddoha & Woodside, 2023). Furthermore, in the realm of disease management, in ovo supplementation with nano-formulated essential minerals like zinc, copper, and selenium has demonstrated promising outcomes in enhancing the post-hatch performance and overall health of broiler chickens (Joshua et al., 2016). The use of cold plasma technology in processing poultry products has also shown to offer benefits in terms of quality and safety, exemplifying the diverse applications of biotechnology in the industry (Gavahian et al., 2019).

The aim of this mini review is to elucidate the critical role of biotechnology in overcoming the myriad challenges faced by the poultry industry, with a particular emphasis on improving disease resistance and growth efficiency. By weaving together evidence from current research, this review intends to showcase the transformative potential of biotechnological innovations in poultry breeding and management. It aims to provide a holistic view of the advancements in genetic manipulation, feed optimization, and disease control strategies, highlighting their implications for enhancing poultry production efficiency and contributing to global food security.

BIOTECHNOLOGICAL ADVANCES AND ACHIEVEMENTS

The advent of CRISPR-Cas9 gene-editing technology has markedly influenced poultry genetics, enabling precise genomic modifications to bolster disease resistance and growth characteristics. This cutting-edge tool facilitates targeted alterations in specific genes associated with desirable traits, thus presenting a robust method for genetic enhancement in poultry (Khwatenge & Nahashon, 2021). Through the application of CRISPR-Cas9, scientists have successfully engineered poultry variants with improved resistance to diseases such as avian leukosis virus, exemplifying the precision and effectiveness of this technology in genetic manipulation (Koslová et al., 2020).

In conjunction with genomic selection—a technique that evaluates the entire genome for markers linked to beneficial traits—CRISPR-Cas9 has expedited the breeding of poultry with superior genetic attributes. This synergistic approach has significantly uplifted production efficiency and sustainability within the poultry industry, marking a leap towards more resilient and productive breeds (Park et al., 2020). The integration of CRISPR-Cas9 in developing genome-edited poultry models with novel attributes further underscores its utility across both agricultural and biomedical domains.

Transgenesis, which involves the introduction of foreign genes into the poultry genome, has been notably enhanced by CRISPR-Cas9. This advancement facilitates the development of poultry breeds with improved productivity and environmental adaptability, thereby optimizing the efficiency of poultry production systems. The merger of transgenesis and CRISPR-Cas9 heralds a new era in poultry genetics, aiming to fulfill the demand for breeds that are both disease-resistant and high-performing.

Addressing the challenge of common poultry diseases such as avian influenza and Marek's disease has been a focal point in genetic research. Through biotechnological advancements, significant progress has been made in obtaining poultry breeds with high disease resistance levels. Key to these achievements has been the utilization of genetic engineering techniques, including CRISPR-Cas9, to institute genetic modifications that bolster disease resistance. This approach has proven successful in generating chickens that exhibit resistance to avian influenza viruses and Marek's disease, showcasing the potential of genetic engineering in producing robust poultry breeds (Bi et al., 2016; Shrestha et al., 2018).

Moreover, genomic selection has been instrumental in pinpointing genetic markers that confer disease resistance, enabling the selection of poultry with enhanced resistance to pathogens. This strategy has contributed to the cultivation of breeds with heightened immunity to diseases such as avian influenza and Marek's disease, underscoring the critical role of genetic markers in disease resistance (Luo et al., 2013; Padhi & Parcells, 2016).

Research into genetic variation among chicken lines with varying susceptibilities to Marek's disease has shed light on the genetic underpinnings of disease resistance. By identifying and mapping quantitative trait loci associated with resistance, researchers have unearthed genes and variants crucial for combatting diseases in poultry (Mountford et al., 2022; Costa et al., 2012). This discovery of specific genetic markers and the elucidation of immune response pathways integral to pathogen defense highlight the complex genetic mechanisms underpinning disease resistance in poultry. These mechanisms include the activation of genes responsible for immune responses and the identification of genetic variations that influence susceptibility to diseases (Calenge et al., 2010; Smith et al., 2020; Zekarias et al., 2002; Gul et al., 2022).

Biotechnological interventions have also played a pivotal role in enhancing poultry growth rates, feed conversion ratios, and meat yields. Developments in dietary formulations that align with the intestinal microbiome and host physiology have led to improvements in growth and feed efficiency, showcasing the symbiotic relationship between nutrition and genetics in poultry production (Pan & Yu, 2013). Additionally, the exploration of keratinolytic bacteria for feather keratin degradation and the identification of genetic markers related to feed efficiency underscore the multifaceted approach to improving poultry production through biotechnology (Riffel et al., 2003; Aggrey et al., 2010).

ETHICAL, REGULATORY, AND PUBLIC ACCEPTANCE CHALLENGES

The implementation of genetic modifications in poultry necessitates a comprehensive consideration of both ethical issues and regulatory landscapes to ensure responsible practice. A primary ethical concern revolves around the welfare of the animals, emphasizing the importance of conducting genetic alterations without inflicting harm or distress on the poultry. The ethical integrity of poultry production hinges on guaranteeing that these modifications enhance, rather than compromise, the health and well-being of the animals (Kilpinen et al., 2013).

Furthermore, the potential environmental ramifications of introducing genetically modified poultry into ecosystems invoke significant ethical concerns. The risk of gene transfer to wild populations and the ensuing ecological disturbances underscore the necessity for meticulous evaluation of the environmental impacts, thus reflecting the broad scope of ethical deliberations in this domain (Nóbrega et al., 2015).

From a regulatory perspective, genetic modifications in poultry are subject to a diverse array of international regulations that dictate the utilization of genetically modified organisms. The process to gain regulatory approval is notably intricate, encompassing rigorous safety evaluations and adherence to a complex set of legal standards (Petracci & Cavani, 2011).

Ethical considerations further extend to the commercial aspects of genetically modified poultry. Issues surrounding transparency, the acceptance of genetically modified products by consumers, and the labeling practices pose questions about informed consumer choice and the ethical obligations of producers to provide clear information (Khwatenge & Nahashon, 2021).

Another area of ethical scrutiny involves the potential for genetic modifications to be exploited for purposes other than enhancing disease resistance or production efficiencies.

The ethical application of these technologies mandates a balanced approach, prioritizing benefits for both the animals involved and the end consumers. It underscores the necessity for a principled and cautious application of genetic modifications, aimed at fostering advancements in poultry production that are ethically justified and socially responsible (Ishii, 2015).

FUTURE DIRECTIONS

Anticipated advancements in the realm of poultry genetics are poised to be shaped profoundly by the evolution of gene editing technologies alongside the integration of artificial intelligence (AI) into genetic selection methodologies. Tools such as CRISPR/Cas9 are on the cusp of achieving heightened levels of precision, facilitating targeted genomic modifications in poultry with enhanced efficiency and accuracy (Khwatenge & Nahashon, 2021). The refinement of these gene editing techniques is likely to usher in the emergence of poultry breeds characterized by superior disease resistance, accelerated growth rates, and increased meat yields, heralding significant improvements in production outcomes (Park et al., 2014).

The deployment of artificial intelligence in the sphere of genetic selection promises to revolutionize poultry breeding strategies. With the capacity to sift through vast arrays of genomic information, AI algorithms are adept at identifying genetic markers associated with desirable phenotypic traits. This capability enables a more streamlined and accurate selection of breeding candidates, optimizing the breeding process towards the development of poultry breeds endowed with enhanced performance attributes (Vrba et al., 2020). The synergy between gene editing technologies and AI-driven genetic selection is anticipated to significantly accelerate the pace of genetic advancements within poultry. AI algorithms stand to offer predictive insights into the potential impacts of specific genetic alterations on poultry characteristics, thereby empowering breeders with the knowledge to execute genetic modifications more strategically (Sid & Schusser, 2018).

This convergence of gene editing and AI technologies is forecasted to drive innovation within poultry genetics, leading to the creation of customized poultry breeds that align with distinct production goals and market demands. Further speculation suggests that future iterations of gene editing tools might enable the rectification of genetic defects or the incorporation of novel traits that enhance adaptability to environmental stressors. Concurrently, advancements in AI could extend to the development of models that simulate the outcomes of genetic crosses, thereby refining the efficiency of breeding programs.

Moreover, the integration of AI in monitoring and managing poultry health in real-time could emerge as a pivotal application, utilizing data analytics to preemptively identify and mitigate disease outbreaks. Such technological progressions hold the promise of not only elevating poultry production metrics but also addressing sustainability challenges by optimizing feed conversion ratios and reducing the ecological footprint of poultry farming.

CONCLUSIONS

In conclusion, the frontier of poultry genetics and breeding is on the brink of a revolutionary transformation, driven by the rapid advancements in gene editing technologies and the integration of artificial intelligence (AI) into genetic selection processes. The refinement of gene editing tools, particularly CRISPR/Cas9, promises a future where targeted genomic modifications are executed with unprecedented precision and efficiency. This progression is expected to yield poultry breeds with enhanced disease resistance, superior growth rates, and improved meat yields, addressing some of the most pressing challenges in poultry production today.

Simultaneously, the adoption of AI in genetic selection is set to redefine breeding programs, leveraging vast genomic datasets to identify markers linked to desirable traits with unparalleled accuracy. This synergy between gene editing and AI not only accelerates the pace of genetic advancements but also opens the door to the development of customized poultry breeds tailored to meet specific production objectives and market demands.

As we stand on the cusp of these technological advancements, it is imperative to recognize the ethical and regulatory implications that accompany the application of such powerful tools. The responsible integration of gene editing and AI into poultry genetics demands a careful balance between innovation and ethical considerations, ensuring animal welfare, environmental sustainability, and consumer safety are paramount.

Furthermore, as the field progresses, continuous dialogue among scientists, regulatory bodies, industry stakeholders, and the public will be crucial in navigating the complexities of implementing these technologies. Transparency, ethical responsibility, and public engagement will play key roles in gaining acceptance and trust in genetically enhanced poultry products.

The future envisioned by these advancements is not without challenges, yet it holds the potential for significant benefits in terms of production efficiency, disease management, and sustainability in the poultry industry. By embracing these technologies judiciously and ethically, the poultry genetics field can contribute to securing global food supplies while adhering to the highest standards of animal welfare and environmental stewardship.

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