Research Report Open Access

Genetic Strategies in Poultry to Combat Environmental Stress: An Analysis Based on GWAS

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Animal Molecular Breeding, 2024, Vol.14, No.1 doi: 10.5376/amb.2024.14.0008

Received: 01 Dec., 2023

Accepted: 15 Jan., 2024

Published: 07 Feb., 2024

Preferred citation for this article:

Lin X.F., and Chen H.Y., 2024, Genetic strategies in poultry to combat environmental stress: an analysis based on GWAS, Animal Molecular Breeding, 14(1): 62-71 (doi: 10.5376/amb.2024.14.0008)

Abstract This study meticulously explores the application of genome-wide association studies (GWAS) in enhancing the adaptability of poultry to environmental stressors and its significant contribution to promoting the sustainable development of the poultry industry. Environmental challenges facing poultry production, including extreme climate conditions, increasingly severe disease threats, and the scarcity of nutritional resources, pose significant threats to their growth, development, and overall health. By deeply analyzing the breakthroughs achieved by GWAS technology in revealing the key genetic factors in poultry's response to these environmental stresses, this study highlights the pivotal role of genetic improvement in enhancing poultry's environmental adaptability. This study further details how the findings from GWAS research can be effectively applied in poultry breeding practices, encompassing both its immense potential and the challenges faced. Moreover, in view of the development of future poultry genetic research and breeding strategies, this study offers an in-depth outlook, especially emphasizing the necessity of continuous technological innovation and the protection of genetic diversity. This is crucial not only for addressing current and future environmental challenges but also for ensuring the long-term development of the poultry industry.

Keywords Poultry industry; Environmental stress; Genome-wide association studies (GWAS); Genetic improvement; Adaptability

As the global population grows and consumption habits change, the poultry industry is facing unprecedented challenges. Among these challenges, environmental stress is one of the most direct and significant factors that have an impact on poultry health and productivity (Oloyo and Ojerinde, 2019). Environmental stresses include extreme climatic conditions, disease outbreaks, unstable supplies of feed resources, and increasing environmental pollution. These pressures not only threaten the well-being and survival of poultry, but also directly affect the quality and supply of poultry products, thereby affecting global food security and agricultural economies.

Faced with these challenges, scientists and livestock farmers have been looking for ways to improve poultry's adaptability to environmental stress. Among them, Genome-wide association studies (GWAS), as a powerful genetic analysis tool, has become one of the key technologies to solve this problem. GWAS can help scientists identify key genetic variations that influence poultry's response to environmental stress by analyzing the association between millions of single nucleotide polymorphisms (SNPs) in the genome and specific phenotypes (Wang et al., 2024). These findings not only deepen researchers' understanding of the genetic basis of poultry adaptation, but also provide new directions for breeding, making it possible to develop poultry breeds that can better cope with environmental stress.

The application of genetic strategies, especially those based on GWAS, provides the poultry industry with an effective way to enhance adaptability. Through precise genetic selection and breeding, poultry's resistance to environmental stresses such as heat stress, disease and nutritional deficiencies can be significantly improved. In addition, these genetic strategies can also help reduce dependence on antibiotics and improve feed conversion efficiency, thereby improving production efficiency and sustainability while ensuring poultry health (Yu et al., 2024).

This study is to use GWAS analysis to deeply explore the genetic response mechanisms of poultry to environmental stress, and how to use these mechanisms to improve the adaptability of poultry through genetic improvement; and to explore how to achieve genetic improvement of poultry while maintaining genetic diversity. to prevent narrowing of the gene pool due to breeding. This study is expected to identify key genetic factors related to poultry adaptability, provide scientific basis and technical guidance for poultry breeding, and ultimately achieve the goal of improving the overall adaptability and production efficiency of the poultry industry to environmental changes. By comprehensively applying advanced genetic analysis technologies such as GWAS, this research hopes to provide innovative solutions to the environmental pressure issues faced by the global poultry industry and promote the sustainable development of the poultry industry.

1 Classification and Impact of Environmental Pressure

In the modern poultry industry, environmental stresses have a significant impact on the growth, performance and overall health of the birds. Environmental stress can be divided into three categories: temperature change and heat stress, disease stress, and feed and nutritional stress. These pressures not only affect the welfare and survival rate of poultry, but also directly affect the quality and quantity of poultry products, thus posing challenges to agricultural production efficiency.

1.1 Temperature changes and heat stress

Extreme temperatures, whether high or low, can have significant effects on poultry physiology. Especially in hot environments, the heat stress response in poultry is activated. The heat dissipation methods of poultry mainly include heat dissipation through breathing and heat dissipation through the skin. However, in high temperature environments, these heat dissipation mechanisms are often difficult to work effectively, leading to an imbalance in the body temperature regulation mechanism. Long-term heat stress can cause problems such as growth retardation, reduced egg production, and reduced immune function in poultry. In severe cases, it can even lead to death (Figure 1). High temperature will also affect the food intake of poultry, further exacerbating the problem of nutritional deficiencies and forming a vicious cycle.

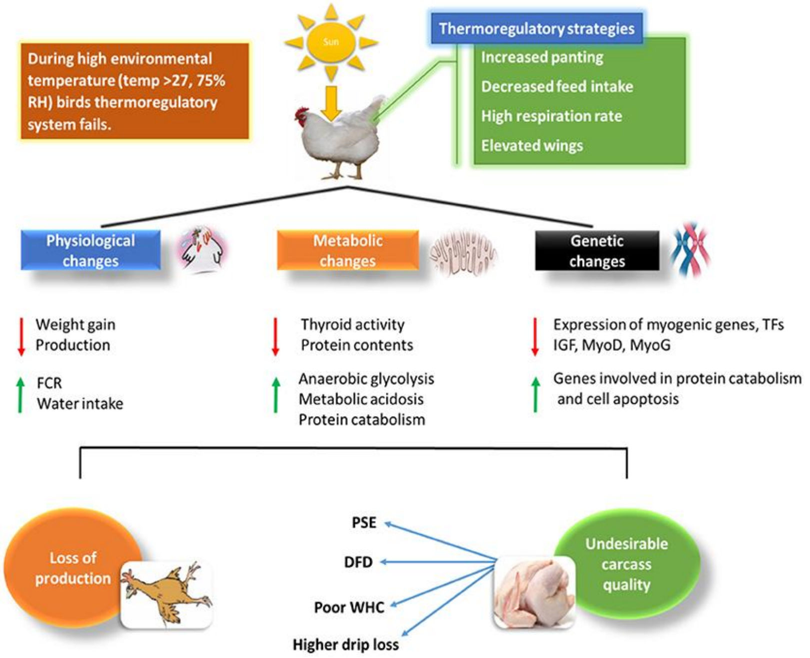

Figure 1 Relationship of HS with physiological and biochemical changes in chicken and how it affects broiler chickens' meat quality (Nawaz et al., 2021)

1.2 Disease pressure

Disease is one of the major environmental stressors that threatens poultry health and performance. Poultry are susceptible to infection by a variety of pathogens during breeding, including bacteria, viruses, and parasites. For example, diseases such as avian influenza, avian cholera and Newcastle disease can not only cause mass deaths of poultry, but also reduce the growth rate and egg production rate of surviving poultry. The outbreak and spread of diseases not only cause harm to individual poultry, but may also lead to a decrease in the production efficiency of the entire breeding group, causing huge economic losses to the poultry breeding industry. Therefore, improving the disease resistance of poultry and preventing the occurrence of diseases through vaccination and improving the breeding environment are the keys to improving the sustainable development of the poultry industry.

1.3 Feed and nutritional pressure

High-quality feed and balanced nutrition are the basis for the healthy growth of poultry. However, in the actual breeding process, poultry often face problems of poor feed quality and insufficient nutrition. The imbalance of nutritional elements in feed will directly affect the growth and development of poultry, leading to growth retardation, reduced immunity, reduced production performance and other problems. Especially for high-yielding poultry breeds, nutritional deficiencies will seriously affect their egg production rate and egg quality. The sustainability of feed resources is also an important consideration, as rising feed production costs and limited resources pose challenges to the long-term development of the poultry industry. Scientifically formulating feeds to ensure balanced nutritional intake by poultry, as well as researching and developing new feed resources, are important strategies to improve poultry production efficiency and cope with environmental pressures (Barszcz et al., 2024).

Faced with extreme temperature changes, disease pressure, and feed and nutritional pressures, the poultry industry needs to take effective management and technical measures to improve poultry adaptability and performance. Through the research and application of advanced genetic improvement technologies, such as genome-wide association studies (GWAS), the key genetic factors for poultry to cope with various environmental stresses can be identified, and then through genetic selection and breeding strategies, healthier and more adaptable birds can be cultivated. Poultry breeds to meet future challenges.

2 GWAS Technology

Genome-wide association studies (GWAS) is a powerful scientific tool that has been widely used in medicine, genetics, and agricultural sciences in recent years. Especially in the field of poultry genetic research, GWAS technology has become a key means to explore and understand how poultry genetically adapt to various environmental stresses.

2.1 Basic principles of GWAS

The core principle of GWAS is to identify genetic markers associated with specific traits by comparing the genomes of different individuals. The process begins by collecting genetic information from large numbers of individuals, often involving hundreds, thousands or even tens of thousands of samples. The researchers used high-throughput sequencing technology to sequence the whole-genome DNA of these samples, and then looked for single-nucleotide polypeptides that appeared frequently in individuals showing specific traits, such as poultry that are better adapted to specific environmental stresses. Physics (SNPs) (Uffelmann et al., 2021). In this way, GWAS can reveal which genetic variants are associated with adaptive traits in poultry.

2.2 Identify key genetic markers

In the study of poultry adaptability, the application of GWAS is extremely important. For example, researchers can use GWAS to identify genetic variants that make poultry better able to withstand heat stress. By comparing the genomes of individuals with high survival rates in high-temperature environments to those of normal individuals, scientists can find specific SNPs associated with heat tolerance. This will not only help to understand the genetic mechanisms of poultry coping with high temperatures, but also guide future breeding programs to select individuals with better genetic adaptability to heat stress for breeding.

The same approach has also been used to identify genetic markers that can improve poultry disease resistance, growth efficiency, meat and egg quality and other traits. Through GWAS analysis, the scientific research team successfully identified some genetic loci related to strong immunity in poultry, which is of great significance for cultivating poultry breeds with stronger disease resistance.

2.3 Limitations and challenges of GWAS research

Although GWAS technology has achieved great success in revealing genetic traits, it also faces some limitations and challenges. GWAS typically require large samples to obtain statistically meaningful results, which in many cases may require a huge investment of money and time. The genetic variants identified by GWAS often explain only a small part of the variation in traits, because many complex traits (such as adaptive traits) are often affected by multiple genetic loci as well as environmental factors.

Even if GWAS successfully identifies genetic markers associated with specific traits, the specific biological mechanisms underlying these markers often remain unclear. GWAS results often require further validation and interpretation through subsequent functional studies. These studies may include gene expression analyses, protein function experiments, and gene knockout or knock-in experiments to reveal how specific genetic variants affect trait expression.

Although the application of GWAS in poultry genetic studies has provided a deeper understanding of the genetic basis, translating these findings into practical breeding strategies remains challenging. Genetic improvement programs need to take into account the effect sizes of genetic variants, interactions between genetic variants, and other potential non-genetic factors.

GWAS technology has become a powerful tool to reveal the genetic basis of poultry adaptation. Despite limitations and challenges, it provides unprecedented opportunities and perspectives for poultry genetic research and breeding (Lee, 2021). By continuously optimizing GWAS methods and combining with other genetics and molecular biology techniques, it is expected that the genetic adaptability of poultry will be more comprehensively understood in the future, thereby guiding more effective genetic improvement strategies and improving the sustainable development capabilities of the poultry industry.

3 Poultry Genetic Improvement Strategies

3.1 Selective breeding

The rapid development of the poultry industry has put forward higher requirements for poultry varieties with high production performance and good adaptability. Selective breeding, a time-honored method, has been the cornerstone of the genetic improvement of poultry. Traditional selective breeding methods focus on selecting breeders based on appearance characteristics or production performance (such as egg weight, growth rate). This method is simple, intuitive, and easy to implement, but its genetic improvement is slow and cannot directly affect the quality of chickens. genes for these traits.

With the development of molecular biology, marker-assisted selection (MAS) technology has emerged. MAS provides a precise genetic selection method for breeding by identifying molecular markers associated with economically important traits. Compared with traditional breeding, MAS can more accurately identify and select individuals with desired genetic characteristics, thus accelerating the genetic improvement process (Boopathi, 2020). Genetic markers related to heat stress tolerance identified through GWAS can be used to select poultry breeds that can better adapt to high temperature environments. MAS not only improves the accuracy of selection, but also greatly shortens the breeding cycle, providing strong technical support for the rapid development of the poultry industry.

3.2 Application potential of CRISPR gene editing technology

In recent years, gene editing technology, especially the CRISPR/Cas9 system, has become a revolutionary tool in genetic research and application. Compared with traditional genetic improvement methods, gene editing technology has the advantages of simple operation, low cost, and high accuracy. It can directly modify the genetic characteristics of poultry at the genetic level, thereby producing individuals with specific traits.

The application potential of CRISPR technology is particularly significant in the genetic improvement of poultry. Using CRISPR technology, scientists can precisely knock out or replace specific genes related to economic traits such as disease susceptibility, growth rate, meat quality, and egg quality, thereby directly improving the production performance and adaptability of poultry (Figure 2). By editing disease-resistant genes, poultry breeds with natural immunity to certain diseases can be bred, which is of great significance for reducing the use of antibiotics and improving poultry health and welfare. In addition, gene editing technology also has great application prospects in improving poultry's stress resistance and adapting to different feeding environments.

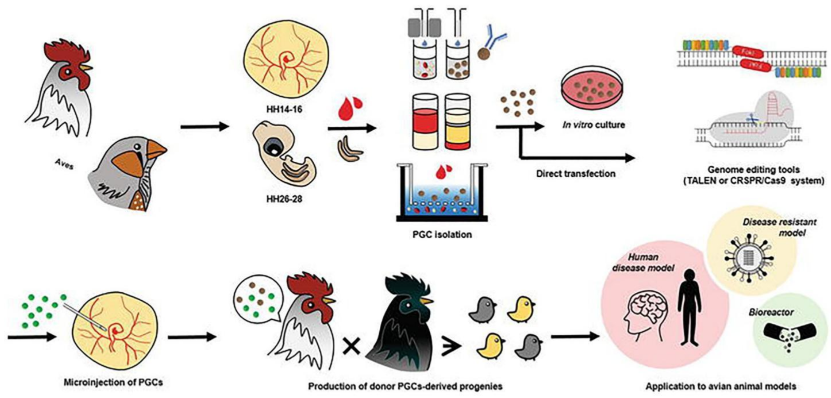

Figure 2 Genome editing in poultry species (Khwatenge and Nahashon, 2021)

Note: Primordial germ cells (PGCs) in poultry can be obtained from embryonic blood and embryonic gonads; Delivery of genome editing tools such as the CRISPR/Cas9 system is followed by the establishment of genome-edited poultry by microinjection of directly isolated or in vitro cultured PGCs into the blood vessels of recipient embryos; Avian genome editing systems can be applied to produce various avian models and poultry

3.3 The importance of genetic diversity in improving poultry adaptability

Genetic diversity is the basis for biological populations to adapt to environmental changes, maintain health and survive. Maintaining or increasing genetic diversity is also crucial during poultry improvement. A high degree of genetic diversity can provide richer genetic resources, making poultry breeds more adaptable and resistant, and able to better cope with environmental changes, diseases and other stresses.

Long-term selective breeding may lead to a reduction in genetic diversity, making poultry populations vulnerable and less adaptable to disease and environmental changes. The protection and enhancement of genetic diversity must be considered in genetic improvement strategies. This can be achieved by introducing genetic material from wild populations, establishing a genetic resource bank, and adopting rotational mating and mixed breeding strategies. By maintaining and improving genetic diversity, not only can the overall adaptability and production performance of the poultry population be enhanced, but it can also provide a wider range of choices and flexibility for future breeding.

Selective breeding, gene editing technology and maintaining genetic diversity are three key strategies in poultry genetic improvement. Each has its own advantages, but the most effective improvement programs often require a combination of these strategies to ensure that poultry breeds are both productive and adaptable to changing environmental conditions. With the continuous advancement of molecular biology technology, poultry genetic improvement will be more accurate and efficient, providing solid scientific and technological support for the sustainable development of the global poultry industry.

4 Challenges and Opportunities in Practice

4.1 Technical and economic challenges

With the increasing application of genome-wide association studies (GWAS) and genetic improvement technology in poultry breeding, researchers face many technical and economic challenges. GWAS requires a large amount of genotype data and precise phenotypic data, which poses a huge challenge to data collection and processing (Tam et al., 2019). In many cases, obtaining a sufficient sample size to ensure statistical power of the study requires a significant investment of time and resources. Although the price of high-throughput sequencing technology has been declining year by year, large-scale application still requires huge investment. Especially for small and medium-sized breeding enterprises, this cost often becomes a difficult threshold to overcome.

The implementation of genetic improvement technologies requires not only a high level of technical expertise but also complex experimental equipment and experimental conditions. These requirements make technology transfer and diffusion more difficult, especially in developing countries. Even in countries with more advanced technologies, these high-end technologies are difficult to be widely used due to the lack of corresponding technical training and support.

From an economic perspective, genetic improvement projects often require long-term return on investment cycles. In the current rapidly changing market environment, such long-term investments may encounter various risks, including changes in market demand, adjustments to policies and regulations, etc. Investors and breeding companies may have doubts about the effectiveness and safety of genetic improvement technology, which further increases project uncertainty.

4.2 Ethical considerations

The ethical issues brought about by genetic manipulation are also challenges that cannot be ignored. Gene-editing technologies such as CRISPR/Cas9 give researchers the ability to alter the genetic characteristics of poultry in extremely short periods of time, sparking ethical discussions about whether humans should interfere with the natural process of evolution. For some, the act of genetically modifying animals touches upon fundamental principles of respect for life.

Public acceptance of genetically modified products is an important issue. Consumers may have doubts about consuming genetically modified poultry products and worry about their safety and health effects, which directly affects the market acceptance of genetically modified poultry products. Therefore, in addition to technology development, scientists and companies also need to invest resources in public education to eliminate misunderstandings, increase transparency, and improve public acceptance.

4.3 Future development direction

Despite the challenges, future developments in genetic research and poultry breeding technology remain promising. With the continuous advancement of genome editing technology and the gradual reduction of costs, it is expected that these technologies will become more popular and their application scope will be further expanded in the future. Especially in terms of disease resistance and growth efficiency, gene editing is expected to bring breakthrough progress (Mortezaei and Tavallaei, 2021).

As people pay more and more attention to animal welfare and sustainable breeding, improving the adaptability and survivability of poultry through genetic improvement and reducing dependence on antibiotics will become an important direction in future breeding. At the same time, based on consumers' requirements for food safety and quality, future genetic improvement technology will also pay more attention to product quality improvement and health attributes.

Interdisciplinary collaboration will be key to advancing genetic research and poultry breeding technology. By combining expertise in genetics, bioinformatics, animal science, and other related fields, research progress can be accelerated while addressing challenges in technology implementation and market acceptance. In the future, this study also looks forward to more policies and legal frameworks to support the healthy development of genetic improvement technology, protect consumer rights, and encourage technological innovation and application.

5 Case Studies

5.1 Successful breeding cases

In poultry genetic improvement projects, several successful cases have demonstrated the great potential of scientific breeding methods to improve yields, disease resistance and adaptability. For example, Torrey et al.'s (2021) broiler chicken improvement project is a typical successful case. Through selective breeding and molecular-assisted selection (MAS) techniques, scientists were able to identify key genetic markers related to growth rate, feed conversion efficiency and meat quality. After several generations of selection, the broiler chickens bred not only grow rapidly, but also have better meat quality and are better able to adapt to different feeding environments.

Another example is the progress in layer breeding. Gao et al. (2022) discovered several genetic loci that affect eggshell strength and egg size through GWAS analysis. These findings were used to guide selective breeding, resulting in laying hen breeds that were both highly productive and capable of producing high-quality eggs. This not only increases the market value of eggs, but also reduces losses during the production process and significantly improves breeding efficiency.

5.2 Application of GWAS in disease resistance research

Disease is a major challenge in poultry production, and genetic improvement offers an effective way to increase poultry's resistance to disease. Genome-wide association studies (GWAS) are particularly useful in this area, helping scientists identify genetic variants associated with disease resistance.

Take avian influenza, for example, a disease that has had a huge impact on the poultry industry. Through GWAS analysis, Drobik-Czwarno et al. (2019) discovered some genetic markers related to avian influenza resistance. These findings were then used in breeding programs with the goal of creating chicken breeds with higher resistance to avian influenza. The application of this method significantly reduces the threat of avian influenza to the chicken industry, while reducing reliance on vaccines and drugs.

Also, there is research on Marek's disease (a viral disease of chickens) (Figure 3). GWAS not only help scientists identify genetic variants associated with disease resistance, but also reveal the complexity of disease resistance mechanisms. These studies provide valuable information for the development of new disease control strategies and guide the implementation of disease-resistant breeding programs.

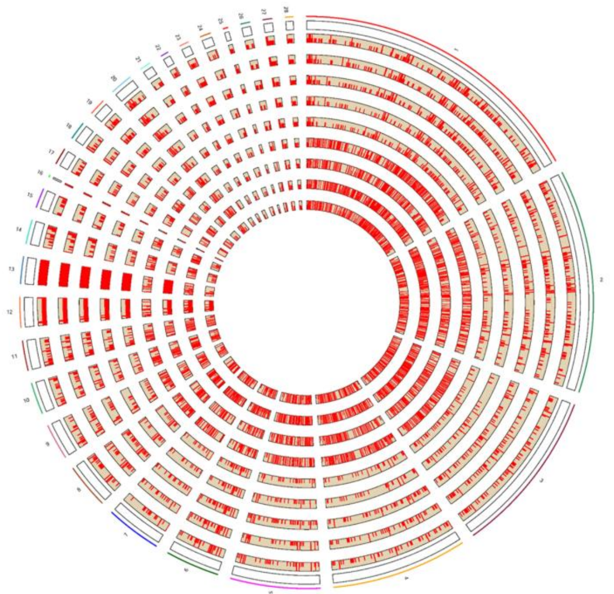

Figure 3 Circos plot illustrating CNV regions in nine chicken lines (Bai et al., 2020)

Note: Regions with copy number events are plotted within the nine light yellow inner tracks; Copy number changes indicated by two different statuses (deletion or duplication) are shown in the inner circle plot using the RCircos; Plot function in RCircos package; The outermost circle displays the chicken chromosomes (chrZ and chrW were excluded); The circles from outside to inside represent Lines 72, 63, F1, RCS-A, M, J, D, L and X

5.3 Future breeding plans

As climate change and environmental pressures increase, future poultry breeding programs will focus more on improving adaptability and sustainability. Towards this goal, scientists are exploring the use of advanced technologies such as GWAS to discover genetic resources that can help poultry adapt to extreme environmental conditions.

One future breeding direction is to improve heat stress tolerance in poultry. As global temperatures rise, the impact of high temperatures on poultry is becoming increasingly severe, so it is particularly important to breed chickens that can maintain high production performance under high temperature conditions. By analyzing genetic variation associated with heat stress tolerance, breeders can more specifically select individuals with these favorable traits for breeding.

Improving the nutrient utilization efficiency of poultry is also one of the focuses of future breeding. With the global shortage of food resources, how to produce more animal products with less feed has become a major challenge facing the breeding industry. Through GWAS technology, scientists hope to find key genetic factors that affect feed conversion rate and nutrient absorption efficiency, so as to guide breeding plans and ultimately breed poultry varieties that utilize feed resources more efficiently.

Future poultry breeding programs will rely even more on advances in genetics and molecular biology. By in-depth understanding of the genetic basis of poultry, combined with advanced breeding technology, researchers are expected to develop efficient and healthy poultry breeds that can adapt to environmental changes and meet market demand.

6 Conclusion

With global climate change and rapid changes in agricultural production conditions, the poultry industry is facing unprecedented challenges. Environmental stresses, such as extreme temperatures, spread of disease, and shortage of nutritional resources, pose severe challenges to the growth and development, production efficiency, and overall health of poultry. Against this background, exploring and implementing effective genetic strategies to improve the adaptability of poultry to environmental stress is not only crucial to maintaining the sustainable development of the poultry industry, but is also of great significance to ensuring global food security and nutritional supply.

Genome-wide association studies (GWAS), as a powerful genetic analysis tool, plays an indispensable role in the research and application of poultry genetic strategies. Through GWAS, researchers can identify genetic markers and genes related to poultry adaptability, providing scientific basis for genetic improvement strategies such as selective breeding and gene editing (Wang et al., 2022). These studies not only help to reveal the adaptation mechanism of poultry to specific environmental stresses, but also open up new ways to improve traits such as disease resistance, growth rate, and heat stress tolerance.

Currently, GWAS has achieved a series of impressive results in poultry breeding. For example, relevant genetic variants identified through GWAS have been used to improve heat stress tolerance and disease resistance in poultry, which is of great significance for improving the living environment of poultry and increasing production efficiency. However, despite significant progress, the potential of GWAS applications in poultry research and breeding is far from being fully exploited.

With the continuous advancement of genome sequencing technology and the further reduction of costs, the application scope of GWAS will be further expanded. This will not only accelerate research on the genetic basis of poultry-related traits, but also promote the implementation of more precise and efficient genetic improvement strategies (Darwish et al., 2019). In addition, with the rapid development of fields such as bioinformatics and computational biology, the ability to analyze and interpret GWAS data will also be significantly improved, and it is expected to reveal the genetic regulatory network of more complex traits.

To realize the full potential of GWAS in future poultry research and breeding, a number of challenges need to be overcome. This includes how to effectively integrate and utilize the growing amount of genetic data, how to improve the accuracy and reproducibility of GWAS studies, and how to resolve ethical and social acceptance issues that may be encountered in genetic improvement. Therefore, future research needs to focus not only on the innovation of technologies and methods, but also on the social impact of the application of these technologies to ensure that the practice of genetic improvement is both scientific, reasonable and socially responsible.

The research and application of poultry genetic strategies, especially the use of GWAS technology, is of great significance to improving the environmental adaptability of poultry. With the continuous advancement of related technologies and the continuous expansion of application fields, GWAS is expected to provide stronger scientific support for the sustainable development of the poultry industry. Future research needs to further explore and exploit this potential to address the challenges posed by environmental pressures and promote innovation and progress in the poultry industry.

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