ID: 467

The Role of Genomics in Improving Egg and Meat Production

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Abstract

Poultry breeding programs have been augmented with technologies such as genome-wide association (GWAS), marker-assisted selection, genomic prediction models, and genome editing (CRISPR/Cas9), creating significant advancement in productivity, resistance to diseases, and quality of products. The aim of this review is to discuss how genomics positively impacts various aspects of egg-and-meat production in poultry. The paper discusses genetic factors that influence traits of major importance, that is, growth rate, efficiency in feed conversion, muscle development, and egg-laying performance, emphasizing domestic breeding aided by molecular tools and bioinformatics as a strategy to accelerate genetic gain. Relevant findings on Norfa chickens, Japanese quail, and indigenous African poultry suggest that breeding strategies can be designed addressing both ecological constraints and economic demands. With beneficial changes, the review acknowledges some challenges, including source data complexity, the ethics of the matter, and the integration of genomic technologies into conventional breeding programs. The discoveries emphasize that meeting the increasing global demand for high-quality animal protein with utmost care for sustaining genetic diversity and resilience within poultry may call for a balanced approach combining state-of-the-art genomics with sustainable management practices.

Keywords: *Egg-meat, Genomics, molecular markers, Poultry.*

1.0 Introduction

There has been a steady increase in the global demand for animal proteins, so much so that the demand for milk and meat products is set to be at 1.25 billion tonnes by 2050 (Ritala et al., 2017) . The current increase in the search for better poultry breeding strategies for increased egg and meat production stems in part from this rising global demand (De Olde et al., 2020). As the human population increases, it applies greater pressure on the poultry industry to produce higher yields, while also regarding efficiency, sustainability, and animal welfare (Kleyn and Ciacciariello, 2021). So far, the traditional selective breeding techniques have brought dramatic improvements in genetic improvement among poultry species, pushing for improvements in productivity. However, these methods are based mainly on observable traits recorded on a long breeding cycle, which limits speed and accuracyy in genetic betterment. Proper genomics can revolutionize poultry breeding by precise genetic selection and better productivity and disease resistance.

Genomics is basically defined as the entire characterization of organisms at the level of their entire genetic makeup, and it provides many different aspects of very important insight into gene functions, interactions and its effects on economically relevant traits in poultry production (Xu et al., 2023). In fact, genomic instruments enable breeders to make genetic data-based decisions rather than phenotype driven decisions (Wolc et al., 2016). This marks a shift of superimposing phenotype-based selection toward genotype-based selection which optimizes growth rate, feed conversion efficiency, egg production, and meat quality genotype in rapid genetic gains in poultry, with further emphasis on long term genetic gain (Vanavermaete et al., 2020). With genome editing technologies like CRISPR/Cas9, genome changes can be made in livestock with efficient precision to improve desirable traits: increased milk yield or improved egg composition. A classic example is the knockout of β-lactoglobulin in dairy cattle producing milk that is hypoallergenic, but with a rich nutritional profile. These advancements greatly assist in meeting the soaring demand for food of animal origin while averting adverse environmental consequences (Yadav et al., 2024).

This review delineates research on genomics for improved egg and meat production across genomic selections, nutrigenomics, and genome-editing technologies. Through rigorous analysis and critique of research findings on the concerned subjects, this paper intends to give a clear view of the role and impact of genomics into nutrition quality, productivity, and resilience of egg and meat production against challenges presented by global food security.

2.0 Genomic Innovations in Poultry Breeding

Many modern breeding tools of genomics, such as genome-wide association studies (GWAS) and genomic selection, have opened the field to the identification and selection of better genetic lines on a much more pragmatic basis (Srivastava et al., 2020). GWAS analyses genetic differences across populations to identify genetic variants linked to important production traits. On the other hand, genomic selection applies high-density molecular markers across the entire genome to predict an animal's breeding value with extremely high accuracy (Wolc et al., 2016; Ren et al., 2024). Compared to selection based on phenotype, genomic selection has massively boosted selection speed and accuracy in breeding programs (Vanavermaete et al., 2020). Consequently, the efficiency of poultry production has also been substantially increased. Enhancements in feed conversion ratio, assessment of skeletal development, and changes in hatchability have been attributed to genomic selection in a commercial context for overall profit in poultry production.

Improving flock health and reducing economic loss is another area where genomics comes in after productivity (Saxena and Kolluri, 2018). Poultry diseases, for example, avian influenza, Newcastle disease, and infectious bronchitis, are some of the most prominent threats to the industry, with mass mortality rates and economic blowbacks (Abdisa and Tagesu, 2017). Advances in genomic research have identified some specific markers for genetic resistance to these diseases so that poultry breeding for resistant strains can be carried out. Incorporating these markers into breeding programs have allowed breeders and poultry producers to boost the natural immunity of these birds (Cheng et al., 2013), minimizing the need for antibiotics and vaccines, which achieves two things; one is that it makes the birds mostly immune to these diseases and secondly by reducing the use of antibiotics it also reduces the cases of antimicrobial resistance, a pressing problem in the world today affecting both humans and animals (Köser et al., 2014).

Genomics influences characteristics such as tenderness, juiciness, and composition of fat on the meat because these are considered by consumers and therefore fall into market value (Leal-Gutiérrez et al., 2020). Transcriptomic analysis and expression profiling have helped researchers pinpoint the key genes involved in muscle development, lipid metabolism, and protein synthesis, for example, identifying the role of myostatin (MSTN) in muscle mass regulation and fatty acid-binding proteins (FABP) in intramuscular fat content that relates to tenderness of the meat (Bennett et al., 2019; Del Pino et al., 2020). Next, precision breeding methodologies are applied to increase the quantity and quality of poultry products while conserving genetic diversity (Huang et al., 2020).

Genomics has also played a role in egg production including laying performance, eggshell quality, and egg size (Li and Tian, 2018). Years of genetic studies have localized and mapped important regions in the genome associated with eggshell strength, yolk composition, and persistence in laying (Goto and Tsudzuki, 2017). New advances in functional genomics have broadened the understanding of genes that control reproduction efficiency, leading to the improvement of layers that have longer and more consistent laying cycles (Bain et al., 2016).

3.0 Genomics Tools and Technologies in Poultry Breeding

3.1 Molecular Genetic Approaches

The identification of candidate genes that determine major traits such as egg production, growth rate, and meat yield and has thus far been one of the most significant achievements in the field of genomics and a well-known molecular genetic approach. Radostina (2024) discussed molecular-genetic approaches in poultry breeding, stating that techniques like GWAS and microsatellite markers have been valuable accessions for establishing the association of genetic variants with traits of economic importance. GWAS, for example, enables the researcher to scan the whole genome for loci that are associated with desirable traits such as body weight or disease resistance (Ren et al., 2024). These findings build a sort of road-map for the breeders to select poultry with certain specific genetic traits relevant with market expectations. Breeders could further combine the genes in fine-tuning their selection programs, speeding up the breeding process and increasing the precision with which desirable traits are incorporated into new poultry lines (Radostina, 2024).

In the molecular genetic toolkit of poultry breeding, molecular markers play an indispensable role. These include microsatellites, single nucleotide polymorphism (SNP), and restriction fragment length polymorphism (RFLP) (Beuzen et al., 2000). Whereas microsatellites are very polymorphic and are good for genetic mapping, SNPs are very ubiquitous within the genome and are good markers of identifying the genetic variation (Miah et al., 2013).

4.0 Genetic Improvement of Egg Production in Poultry

One of the primary studies that has provided compelling evidence of genetic improvement in poultry emerges from research carried out at Menoufia University, where Norfa chickens were studied for over two generations with respect to the heritability and improvement of egg production traits. The experimental design involving the division of the base population into selected and control lines showed that further strategies of breeding aimed at egg production through a selection index method were able to enhance productivity significantly. Key management practices such as feed adjustment and a lighting program based on "step down-step up" also played considerable roles in the optimization of laying performance in Norfa hens, indicating the equivalency of genetic versus environmental factors involved in poultry production.

In sharp contrast, a long-term study was also performed on Japanese quail (Nandanam quail-3) across six generations to improve egg production traits through a multi-stage selection process (Pandian et al., 2022). Here, the report showed that hen housed egg production had been significantly enhanced with an increase from 202 to 220 eggs over 40 weeks of laying, with a high goodness of fit ($R^2 = 0.97$). Notably, a negative correlation was exhibited between body weight and egg production traits, which, the multi-stage selection strategy successfully addressed, resulting in enhancement of both traits.

4.1 Indigenous Chicken Production and Disease Resistance

Research by Zhou et al. (2024) explored the enhancement of egg production traits in African village chickens, with an emphasis on resilience to Newcastle disease (ND). The Feed the Future Innovation Lab for Genomics to Improve Poultry developed a genetic selection platform designed to improve survival rates, reduce virus shedding, and enhance both growth rates and egg production in these chickens. Unlike the controlled breeding environments of the Norfa and Japanese quail studies, this research highlighted the challenges posed by real-world production systems, where disease resistance and adaptability to environmental stressors are critical. The study's findings suggest that integrating genetic selection for ND resistance with traditional vaccination and biosecurity measures offers a promising avenue for improving egg production in indigenous poultry lines.

4.2 Genome-Wide Association Study in Qingyuan Partridge Chickens

Another level of insight was brought into genetic improvement for egg production by the recent genome-wide association study (GWAS) done on Qingyuan partridge chickens (Kang et al. in 2024). The research identified MTA2 as a potential new candidate gene responsible for the egg laying rate in laying hens. Notably, this is the first time that this gene has been associated with traits for egg production in chickens. Further, one genomic-significant SNP and three chromosomal significant single nucleotide polymorphisms (SNPs) correlated with egg laying rate were found, indicating that whole genome resequencing is an efficient way to identify genetic markers accurately. The genetic enhancement of traits pertaining to egg production can be furthered by molecular genetics techniques.

5.0 Genetic Improvement of Meat Production in Poultry

Growth rate and feed conversion ratio (FCR) are two very economically relevant traits in broiler chickens. Selection programs have seen much progress in the improvement of these traits over the past several decades. Genetic factors concerning growth are associated with key regions of the chicken genome; comparatively, quantitative trait loci (QTL) studies indicate specific markers for faster weight gain and better feed efficiency (Cahyadi et al., 2014). For example, the insulin-like growth factor-I (IGF1) gene is vital for growth and feed utilization. By means of marker-assisted selection (MAS), the favourable alleles of IGF1 and similar genes can be incorporated by the breeder to improve growth performance without compromising health or reproductive traits (Dou et al., 2022).

Genomic selection, in addition to being based on estimated breeding values (EBVs), allows for multiple-trait advancement such as rapid growth with optimal FCR while avoiding adverse effects such as leg disorders or cardiovascular problems (Xu et al., 2020). Thus, the entire concept is about making genetic progress that will sustain the poultry producer and also be good for the bird (Fleming et al., 2007).

5.1 Muscle Development and Meat Quality

A key aspect of genetic enhancement in broiler chickens refer to muscle development and meat quality. Rapid growth is desirable but needs to be combined with the required texture, flavour, and tenderness of meat, according to consumer preferences (Mir et al., 2017). Many candidate myogenic genes and muscle fibre characteristics have been identified through advanced techniques in molecular genetics (Joo et al., 2013). For instance, the myostatin (MSTN) gene is one of the most prominent muscle regulators, and MSTN inhibition or downregulation can result in an increase in muscle mass—an indicator in the meat production feature. Expression of MSTN must be done carefully to eliminate problems such as muscle hypertrophy that adversely affect meat quality or animal welfare.

Additionally, genes regulating postmortem glycolysis in muscle pH, for example, AMP-activated protein kinase (AMPK) pathway genes, also play major roles in the tenderness of meat and water-holding capacity (Scheffler et al., 2011). Breeders can select for favourable variants of these genes to gain benefits from both yield and sensory quality of poultry meat.

5.2 Fat Deposition and Carcass Quality

As we understand it, fat distribution and carcass yield are the most important traits in broiler production, influencing processing efficiency and, hence, consumer satisfaction (Mir et al., 2017). According to Moreira et al. (2018), Genomics research has reported much of the genetic understanding of the mechanisms whereby fat is deposited and lean meat is produced, such that more accurate selection for these traits is now possible. The gene involved in peroxisome proliferator-activated receptor gamma (PPARG) marks the entry point in the regulation of adipogenesis, making mutations here consequential to the regulation of the balance between fat and muscle growth (Fredenrich and Grimaldi, 2004). Thus, breeders could increase the quality of carcasses by excluding alleles caused by excessive fat deposition, which leads to increased feed inefficiency. From GWAS, SNPs have been detected that were significantly associated with abdominal fat percentage and breast muscle yield, two of the major traits considered in the optimization of broiler carcass composition.

6.0 Challenges and Limitations of Genomic Applications

The sheer complexity of genomic data is one of the most remarkable technical barriers. The bulk of information produced by genomic sequencing makes its accurate analysis and interpretation rather tedious and, thus, tends to create delays and even possible misdiagnoses. Moreover, protein stability prediction—an important factor with respect to precision medicine—is still a challenging exercise mostly because of scant thermodynamic data and variability in experimental conditions. This lack of predictively accurate assays precludes the establishment of definitive therapeutic interventions pertaining to proteins for research use (Sanavia et al., 2020).

7.0 Conclusion

The genetic improvement of poultry production, whether for egg or meat yield, represents a remarkable convergence of traditional breeding practices and modern genomic technologies. It enhances productivity, disease resistance, and economic viability in poultry farming. Techniques like selective breeding, molecular genetics, and genome-wide association studies (GWAS) optimize egg and meat production traits, even in the face of environmental and disease-related challenges. However, challenges such as data complexity, ethical considerations, and organizational difficulties present challenges. As genomic technologies continue to evolve, their thoughtful application promises to shape a more efficient and resilient poultry industry, supporting global food security and economic development.

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