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Genetic Selection for Advances in Meat Quality

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Abstract

The ever-growing consumer demand for high-quality meat products has resulted in the need for progressive improvement of meat quality traits in livestock, often at an economic cost. Genetic selection has transformed livestock breeding, enabling the improvement of meat quality traits such as tenderness, marbling, flavor, and juiciness. Advances in genomic technologies, including genome-wide association studies (GWAS)**,** marker-assisted selection (MAS)**,** and genomic selection (GS)**,** have enhanced the precision of breeding strategies. Recent studies are reviewed, focusing on the genetic determinants of meat quality, advances in genomic selection, and the potential use of CRISPR-based gene-editing technologies for precision genetics breeding.

Keywords: Genetic selection, Meat quality, Marbling, Tenderness, Genome-wide association studies (GWAS), Marker-assisted selection (MAS), Livestock breeding

Introduction

Meat quality is a vital aspect of livestock production, influencing consumer preference, market value, and industry sustainability. In 2023–24, India produced 10.25 million tonnes of meat, reflecting a 4.95% increase from the previous year and a 4.85% growth over the past decade. West Bengal contributed the highest share (12.62%), followed by Uttar Pradesh (12.29%) and Maharashtra (11.28%). Poultry accounted for the largest portion (48.96%), while buffalo, goat, sheep, and pig contributed 18.09%, 15.50%, 11.13%, and 3.72%, respectively. Traditional breeding methods have focused on growth rates and feed efficiency; however, recent advances in genetic selection provide an opportunity to directly enhance meat quality traits. Understanding the genetic basis of meat characteristics enables breeders to make informed decisions that align with both industry demands and consumer expectations. Environmental factors such as feed type, health management, and processing methods also play a crucial role in determining key meat quality attributes, including tenderness, marbling, water-holding capacity, and color (Haque et al., 2025). While conventional breeding has improved production efficiency, advancements in genomics offer valuable tools to optimize meat quality traits (Wei et al., 2025). This review aims to provide insight into genetic selection approaches, recent advances in genomic selection, and breakthrough technologies to optimize meat production in livestock.

Genetic Basis of Meat Quality

Key Meat Quality Traits

- **Tenderness:** A crucial determinant of meat quality, influenced by muscle fiber composition, collagen content, and post-mortem proteolysis (Salatta et al., 2025).
- **Marbling (Intramuscular Fat Content):** Impacts flavor, juiciness, and nutritional value; associated with genes such as CAST (Calpastatin), DGAT1 (Diacylglycerol O-acyltransferase 1), and LEP (Leptin) (Arikawa et al., 2025).
- **Meat Color:** Determined by myoglobin content and oxidative metabolism; genetic studies have identified markers linked to resistance against meat discoloration (Villalobos-Cortés et al., 2024).
- **Water-Holding Capacity:** Affects juiciness and cooking yield, regulated by PRKAG3 (Protein Kinase AMP-Activated Gamma 3 Subunit) (Wang et al., 2025).

Candidate Genes and Molecular Markers

Recent GWAS and transcriptomic studies have pinpointed genetic markers associated with superior meat quality traits:

- **CAPN1 (Calpain 1) & CAST (Calpastatin):** Regulate post-mortem muscle proteolysis, impacting tenderness in beef and pork (Shi et al., 2025).
- **FTO (Fat Mass and Obesity-Associated Gene):** Influences lipid deposition and marbling in beef cattle (Zayas et al., 2025).
- **ADIPOQ (Adiponectin Gene):** Plays a key role in fat metabolism, contributing to pork quality (Peng et al., 2025).

These findings provide a foundation for precision breeding programs aimed at improving meat quality while preserving genetic diversity.

Advances in Genetic Selection Technologies

1. **Marker-Assisted Selection (MAS)**

MAS utilizes DNA markers to select economically important traits, reducing reliance on phenotypic assessments. Studies have shown that MAS improves meat tenderness and marbling efficiency in cattle (Wu et al., 2024).

2. **Genome-Wide Association Studies (GWAS) & Genomic Selection (GS)**

- GWAS has identified **SNPs (single nucleotide polymorphisms)** associated with muscle fiber type, fat deposition, and oxidative metabolism (Colombi et al., 2025).
- **Genomic Selection (GS)** integrates whole-genome information into estimated breeding values (EBVs) to accelerate genetic improvements (Haque et al., 2025).
- GS has already been successfully applied to improve carcass traits in Hanwoo cattle (Haque et al., 2025).

3. **CRISPR and Gene Editing in Livestock**

CRISPR-Cas9 is a precise genome-editing tool that allows targeted gene modifications in livestock:

- **MSTN (Myostatin) Deletion:** Enhances muscle growth and lean meat production in cattle and pigs (Guo et al., 2025).

- **FASN (Fatty Acid Synthase) Knockout:** Improves healthy fat profiles in pork (Khatkar et al., 2024).

While CRISPR has the potential to revolutionize livestock breeding, ethical and regulatory concerns must be addressed through further research.

Implications for Livestock Breeding Programs

A. **Economic and Industry Impact**

- The integration of genomic tools into breeding programs has led to:
- Improved meat quality consistency
- Increased economic returns for farmers
- Enhanced feed efficiency and sustainability (Velleman & Strasburg, 2025)

B. **Ethical and Sustainability Considerations**

- Over-reliance on genetic selection may reduce genetic diversity, increasing susceptibility to disease (Li et al., 2025).
- Consumer perceptions of genetically modified meat must be addressed through transparent labeling and education (Jo et al., 2025).

Challenges

Despite the progress made in genetic selection for meat quality, several challenges remain. One of the primary concerns is the potential trade-off between productivity traits, such as growth rate and feed efficiency, and meat quality traits (Schenkel et al., 2018). Selecting for improved meat quality may inadvertently reduce the genetic progress in traits related to production efficiency, leading to economic challenges for producers. To address this, integrative breeding programs that incorporate both productivity and quality traits are essential. Additionally, the identification of genetic markers for meat quality traits remains incomplete, and the polygenic nature of these traits complicates the selection process. Ongoing research is needed to identify novel genetic variants associated with meat quality and to better understand the genetic architecture of these traits (Zhang et al., 2019).

Conclusion and Future Perspectives

Genetic selection has revolutionized meat quality improvement through GWAS, MAS, and gene editing. However, future research should focus on:

- Multi-omics approaches (genomics, transcriptomics, and epigenetics) to refine trait selection.
- Establishing ethical guidelines for CRISPR applications in livestock.
- Consumer-driven breeding programs aligning genetic selection with market demands.
- By integrating advanced genetics with sustainable breeding strategies, the livestock industry can ensure the production of high-quality, ethically sourced meat for future generations.

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