

Research on enhancing the market competitiveness of economically important aquaculture species through directed breeding strategies

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Abstract. With the continued growth in global demand for aquatic products, the traditional development model based on natural populations and experience-driven farming practices can no longer meet the modern aquaculture industry's requirements for high productivity, efficiency, superior quality, and sustainable development. As a key approach to modern genetic improvement in aquaculture, directed breeding employs genetic selection for target traits, including growth rate, feed utilization efficiency, disease resistance, environmental adaptability, and nutritional quality, thereby significantly enhancing the overall production performance and market competitiveness of commercially important aquaculture species. In recent years, advances in genomics, Marker-Assisted Selection (MAS), genomic selection, and precision nutritional regulation have driven the transition of directed breeding in aquatic animals from conventional phenotypic selection to precision breeding. This paper systematically examines the current applications of directed breeding in commercially valuable aquaculture species, with particular emphasis on recent progress in optimizing growth performance, improving nutritional quality, enhancing stress resistance, and increasing market value. A review of the literature and representative case studies indicates that directed breeding can increase the growth rate of cultured species by 10%–20% and improve feed conversion efficiency by more than 15%, while significantly enhancing protein content, the composition of unsaturated fatty acids, and the stability of product quality, thereby strengthening market competitiveness. In addition, integrated breeding strategies combining genomic selection with precision nutrition are emerging as a major direction for future industrial development. The study suggests that establishing a synergistic framework integrating genetic improvement, nutritional optimization, and market value enhancement is a key pathway for promoting the high-quality development of modern aquaculture.

Keywords: aquaculture, directed breeding, genetic improvement, nutritional quality, market competitiveness

1. Introduction

Directed breeding has emerged as a central driving force behind genetic improvement in modern aquaculture, fundamentally reshaping the market competitiveness of commercially important aquatic species through the integration of genomics, Marker-Assisted Selection (MAS), and precision nutritional regulation technologies.

Traditional production systems, which rely heavily on the exploitation of natural populations and experience-based farming practices, are increasingly unable to satisfy the growing global demand for aquatic products characterized by high productivity, efficiency, and quality. Directed breeding strategies based on multi-omics data not only improve growth rate, Feed Conversion Ratio (FCR), disease resistance, and nutritional quality, but also establish significant technological and commercial advantages in the highly competitive global seafood market [1, 2]. Recent studies have demonstrated that systematic genetic selection can increase the growth rate of cultured species by 10%–20% and improve feed conversion efficiency by more than 15%, while substantially enhancing muscle protein content and the composition of unsaturated fatty acids, thereby directly increasing the added market value of aquaculture products [3, 4].

2. Innovative applications of genomic selection and molecular breeding technologies

The widespread adoption of Genomic Selection (GS) has marked a paradigm shift in aquaculture breeding from phenotype-based selection to genotype-based selection. Genome-Wide Association Studies (GWAS) enable researchers to identify specific genomic regions and Single Nucleotide Polymorphisms (SNPs) closely associated with economically important traits, thereby linking molecular markers to Quantitative Trait Loci (QTLs) and incorporating them into breeding programs [5]. For example, in tiger puffer (*Takifugu rubripes*), genomic prediction using low- and medium-density SNP panels has demonstrated high predictive accuracy for traits such as testis weight, body length, and body weight. Moreover, these studies have shown that reducing the number of SNP markers can substantially lower genotyping costs while maintaining satisfactory prediction accuracy [6]. In European seabass (*Dicentrarchus labrax*) and gilthead seabream (*Sparus aurata*), optimizing the size of training populations and marker density has significantly improved the accuracy of genomic predictions for disease resistance, providing a cost-effective and efficient genetic strategy for mitigating disease outbreaks that pose a major threat to the aquaculture industry [7]. In addition, the construction of high-density genetic linkage maps has accelerated the identification of QTLs associated with growth traits in species such as Japanese meagre (*Argyrosomus japonicus*), laying the groundwork for the fine mapping of key functional genes [8].

The integration of Marker-Assisted Selection (MAS) with conventional breeding approaches is overcoming long-standing bottlenecks in the improvement of complex traits. In the development of salt-tolerant strains of species such as tilapia, the combination of traditional and molecular breeding technologies has accelerated the production of varieties adapted to brackish and marine aquaculture environments, an advancement of considerable strategic importance for alleviating freshwater resource constraints [9]. In the banana shrimp (*Penaeus merguensis*), studies employing SNP markers for sibship assignment have demonstrated that high-throughput sequencing technologies can effectively resolve the pedigree structure of large spawning populations, thereby facilitating the management of genetic diversity and ensuring sustained long-term selection responses [10]. Likewise, the development of a haplotype reference panel for genotype imputation in the Chinese scallop (*Chlamys farreri*) has further improved the efficiency and accuracy of genomic selection [11]. These technological advances are not confined to finfish but have also been successfully extended to crustaceans and molluscs, highlighting the broad applicability of genomic tools across aquaculture breeding programs [12].

As a frontier technology in directed breeding, gene editing offers an unprecedented level of precision for the direct improvement of economically important traits. Using gene-editing platforms such as CRISPR/Cas9, researchers can precisely modify target genes to enhance growth performance, disease resistance, and

environmental adaptability [13]. Unlike conventional transgenic approaches, gene editing can exploit naturally occurring genetic variation without necessarily introducing exogenous DNA. Although regulatory frameworks and public acceptance of these technologies continue to evolve, their potential to accelerate genetic improvement is considerable [14]. In addition, line breeding and hybridization remain important strategies for protecting intellectual property and maintaining desirable genetic traits. In species such as tilapia and Asian seabass, these approaches, while resource-intensive, can generate substantial long-term gains in productivity and sustainability [15].

3. Achievements in the directed improvement of key economic traits

3.1. Growth performance and feed conversion efficiency

Genetic improvement of growth performance and Feed Conversion Efficiency (FCR) is a key driver of sustainable development in aquaculture. Growth rate and feed efficiency directly determine the length of the production cycle and the input–output ratio, with feed costs typically accounting for 50%–65% of total variable production costs [16]. Studies on species such as Pacific white shrimp and flounder have demonstrated that directed breeding, through both genomic selection and conventional breeding approaches, can significantly accelerate genetic gains in growth-related traits, thereby increasing biomass production per unit of culture area [17–19]. Meanwhile, integrated multi-omics approaches combining transcriptomics and metabolomics are providing deeper insights into the molecular mechanisms underlying feed conversion efficiency, establishing a solid theoretical foundation for reducing feed costs through genetic improvement [16, 20, 21]. Under identical rearing conditions, improved strains exhibit higher feeding efficiency and superior nutrient utilization, directly enhancing production profitability while reducing the environmental impact associated with nutrient discharge [4, 22].

The application of genetically improved strains not only enhances growth performance but also significantly improves resource-use efficiency and environmental sustainability. Studies on elite genotypes of European seabass (*Dicentrarchus labrax*) have shown that combining genetic improvement with nutritional innovation can further optimize growth performance and feed utilization, even when alternative protein sources are incorporated into aquafeeds [4, 23]. In tilapia culture, substantial differences in growth performance have been observed among strains under pond farming conditions, with selected lines exhibiting higher specific growth rates and lower feed conversion ratios in particular production environments [24, 25]. Furthermore, integrating alternative protein ingredients, such as single-cell proteins and plant-based proteins, with selective breeding strategies can effectively reduce dependence on fishmeal while maintaining or even improving growth performance and flesh quality [23, 26]. Functional feed additives, including yeast hydrolysates and chitosan-based nanocomposites, have also been shown to indirectly enhance growth performance and feed efficiency by modulating gut microbial communities and improving immune status [27–29].

3.2. Disease resistance and environmental adaptability

The intensification of global climate change and the widespread adoption of intensive aquaculture systems have exposed aquatic organisms to the dual challenges of disease outbreaks and environmental stressors, including hypoxia and salinity fluctuations. Consequently, traditional single-trait breeding strategies are gradually being replaced by multi-trait selection and genomic breeding approaches aimed at developing superior strains that combine enhanced disease resistance with strong environmental adaptability. Recent studies have demonstrated that integrating conventional breeding with modern genomic technologies has

achieved significant progress in improving resistance to specific pathogens, such as *Cryptocaryon irritans* and *Vibrio* species, as well as tolerance to environmental stressors including hypoxia and high salinity. These advances not only increase survival rates but also strengthen the resilience of aquaculture production systems to extreme environmental fluctuations [30–32].

Among marine fish, the large yellow croaker (*Larimichthys crocea*), one of China's most economically important cultured species, provides a representative example of disease-resistance breeding. White spot disease caused by *Cryptocaryon irritans* is a major constraint on large yellow croaker production. Studies have shown that genomic selection over two successive generations can significantly enhance resistance to this parasite, with the trait exhibiting a strong genetic basis [33]. Using a 20K SNP array developed for the species, Genome-Wide Association Studies (GWAS) have successfully identified Quantitative Trait Loci (QTLs) associated with resistance to *C. irritans*, providing precise targets for marker-assisted selection [34, 35]. In addition, evidence of genetic linkage between swimming performance and disease resistance offers a theoretical basis for multi-trait breeding strategies, making it possible to improve disease resistance without compromising growth performance [36].

Significant advances have also been achieved in disease-resistance breeding for aquatic invertebrates. In the Pacific oyster (*Crassostrea gigas*), estimates of genetic parameters for resistance to *Vibrio alginolyticus* infection indicate moderate to high heritability, suggesting that family-based selection can rapidly improve population resistance [37]. Selective breeding programs targeting summer survival have likewise demonstrated the effectiveness of genetic improvement in reducing mortality during periods of elevated temperature [38]. In scallop culture, resistant larvae have been found to harbor host-associated bacterial communities with probiotic potential, while disease-resistant individuals exhibit constitutive expression of immune-related genes and enhanced antimicrobial responses. These findings provide a new perspective on integrating microbiome regulation into selective breeding programs [39, 40].

Environmental adaptability, particularly tolerance to salinity fluctuations and hypoxia, has become another major breeding objective. As an emerging aquaculture species, the spoon worm (*Urechisunicinctus*) has shown considerable potential for selective improvement, with heritability estimates for body length and body weight under low-salinity stress indicating that enhanced salinity tolerance can be effectively achieved through genetic selection [41]. Hypoxia tolerance has become increasingly important in response to eutrophication and oxygen depletion associated with intensive aquaculture practices. Declining dissolved oxygen concentrations have been shown to adversely affect the survival, metabolism, and reproductive performance of aquatic organisms, making the development of hypoxia-tolerant strains an urgent priority [42]. In the large yellow croaker, analyses of DNA methylation and gene expression under hypoxic conditions have revealed the critical role of epigenetic regulation in hypoxia adaptation, with differential methylation of specific genes closely associated with tolerance to oxygen deficiency [43]. Similarly, physiological and transcriptomic analyses of the Manila clam under varying salinity stresses have elucidated mechanisms of osmoregulation, demonstrating that Na^+/K^+ -ATPase activity and compatible solute accumulation pathways play central roles in maintaining cellular homeostasis [44].

3.3. Improvement of nutritional quality and market value

As consumer demand shifts toward higher-quality aquatic products, directed breeding has expanded beyond the pursuit of increased yield to encompass the optimization of muscle nutritional composition, including protein content, amino acid profiles, and the proportion of polyunsaturated fatty acids [3, 23]. Genome-wide association studies targeting economically important quality traits, such as glycogen content in abalone, have demonstrated that selection for specific SNP loci can effectively improve product texture and nutritional value,

thereby meeting the demands of premium markets [45]. To objectively evaluate improvements in sensory quality, electronic tongue technology has been increasingly adopted for the assessment of flesh flavor characteristics. Compared with traditional sensory evaluation panels, electronic tongue systems provide rapid, objective, and highly reproducible measurements of taste attributes [46, 47]. In studies of European seabass, electronic tongue analyses have confirmed that specific genotype–diet combinations can significantly enhance flesh flavor profiles. By quantifying fundamental taste characteristics, including umami, sweetness, and bitterness, researchers have elucidated the mechanisms through which dietary modifications influence non-volatile flavor compounds in muscle tissue [48, 49]. Beyond validating substantial improvements in sensory quality, this technology provides a scientific basis for establishing instrument-based quality grading systems, thereby enhancing the competitiveness of aquaculture products in high-value markets [50, 51].

4. Synergistic breeding systems and future prospects

Future developments in directed breeding for aquaculture are expected to move toward a synergistic framework integrating genetic improvement, nutritional optimization, and market value enhancement. Gene-editing technologies, particularly CRISPR/Cas9, provide novel opportunities for the rapid introduction, modification, or knockout of genes associated with economically important traits. Although regulatory and ethical issues surrounding these technologies continue to evolve, their potential to accelerate breeding progress is substantial [52, 53]. At the same time, cost-effective genotyping strategies, such as the combination of low-density SNP panels with genotype imputation techniques, are making genomic selection economically feasible for a wider range of small- and medium-scale breeding programs [54, 55]. Furthermore, the integration of artificial intelligence and big data analytics with multi-omics breeding platforms is expected to further improve predictive accuracy, facilitating the transition from single-trait selection to comprehensive multi-trait selection indices [17, 56]. Taken together, directed breeding, through the precise manipulation of genetic potential in combination with precision nutritional management, is reshaping the entire aquaculture value chain. By simultaneously improving production efficiency, product quality, and consumer value, this integrated approach is expected to substantially strengthen the global market competitiveness of commercially important aquaculture species.

5. Conclusion

Directed breeding, through the integrated application of genomic selection, marker-assisted selection, and gene-editing technologies, has substantially improved growth performance, feed conversion efficiency, disease resistance, and nutritional quality in commercially important aquaculture species. Practical evidence indicates that multi-omics-based breeding strategies enable the precise improvement of key economic traits while offering significant advantages in reducing production costs, enhancing resilience to environmental stress, and meeting the growing demand for premium-quality aquatic products. Looking ahead, the establishment of a synergistic breeding system that integrates genetic improvement, nutritional regulation, and market value enhancement, together with the adoption of low-cost genotyping technologies and artificial intelligence-assisted analytical tools, will further advance the precision and intelligence of aquaculture breeding. Such an integrated framework is expected to provide a fundamental driving force for strengthening the long-term sustainability and global competitiveness of the aquaculture industry.

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