Aquaculture Reimagined: Modern Approaches to Sustainable Fish Farming
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Chapter 5

Genetic Improvement: Breeding for Better Aquaculture

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Abstract

As aquatic food demand continues to increase globally and with the unexplored wild fish resources depleting rapidly expansion of aquaculture is needed to meet the demand. Genetic improvement breeding has come as an important tool that is aimed at increasing the efficiency and sustainability of aquaculture. Selective breeding, crossbreeding, hybridization, genetic engineering and other techniques are employed to increase the growth rate, disease resistance and adaptability to climate changes among other economically important traits. Although significant achievements have been made in some of the fish like the Atlantic salmon, tilapia and craps where these species are farmed to grow faster and improved disease resistance. Advanced molecular genetics like marker-assisted selection (MAS) and genomic selection have been employed in breeding programs that help more efficiently in trait selection. Genome editing technologies, specifically the CRISPR/Cas9 system, offer more innovative information. In addition, sustainability is another important factor to consider in the design of future breeding programs. Factors like nutrient pollution, habitat loss and genetic pollution from the domesticated strains escaping to the wild are some of the growing problems and also the lack of sufficient information on phenotypic and genotypic in many cultured species limited the potential use of breeding programs, indicating that data gathering and assessment must be done to increase progression. The chapter provides information on the techniques and technology used in aquaculture breeding. It also provides some insights regarding the challenges and environmental factors when such methods are involved.

Keywords CRISPR/Cas9, Crossbreeding, Genetic engineering, Hybridization, MAS, Selective breeding

1. Introduction

With the increase in the demand for aquatic food, aquaculture has become one of the key solutions due to the depletion of wild fish resources. For

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example, it is projected that fish consumption will increase by about 1.2% per year until the year 2030 when aquaculture will be fundamental in meeting this gap (Salin *et al.*, 2018). Aquaculture can be optimized only through the genetic enhancement of the different species in the sector which includes improving the growth rate, disease tolerance and climate adaptation among other factors. In contrast to land-based Agriculture, nearly 45% of farmed aquaculture species are genetically pure, that is, they are very similar if not identical with their wild counterparts (FAO, 2024). The application of genetic improvement techniques especially selective breeding is on the rise in aquaculture because of the ability to improve desirable traits across generations. However, such selective breeding programs in aquaculture are less advanced as compared to those for livestock or crops because of the shorter period of domestication and genetic traits complexities of aquatic organisms (Du *et al.*, 2021). In addition, most fish and shellfish breeding schemes have been primarily concerned with increasing production and improving growth performance, but are also widening to include disease resistance and the ability to withstand environmental stresses (Huang *et al.*, 2023).

Selective breeding is a process that focuses on raising specific traits of individuals through selective mating of individuals possessing the desired traits. Among such traits are fast growth, high yield and disease resistance. Despite traditionally involving the use of the phenotypic selection approaches in practice, modern-day practices have also developed molecular genetics tools, molecular markers, genome-wide selection and CRISPR-based genome editing systems (Kashyap *et al.*, 2024; Puthumana *et al.*, 2024). These techniques, however, enhance the accuracy of the required genetic modifications, hence slowing down the entire breeding process, but increasing the accuracy of the trait's selection (Huang *et al.*, 2023).

The selective breeding of fish has seen remarkable achievements, particularly with aquaculture species such as tilapia, salmon and carp. For example, some genetically improved strains of tilapia have recorded a 10-17% body weight increase per generation purely because of selective breeding and as well enhancement of growth and disease resistance has been reported among the Atlantic salmon selective breeding (Kashyap *et al.*, 2024). On the other hand, challenges for effective breeding programs remain as such due to reproduction cycles, phenotypic variability and genetic diversity of aquatic organisms (Du *et al.*, 2021).

This chapter will examine the different methods of genetic enhancement applied in aquaculture, with particular emphasis on selective breeding and its significance in increasing the effectiveness, sustainability and fitness of the sector. It will also discuss the challenges associated with genetic selection as well as the possible ways of utilizing genetic modification techniques in aquaculture in the future.

2. Overview of Genetic Improvement Breeding

Heritability: It is an amount of phenotypic variation in a population that results in individual genetic differences. For example, if heritability (h2) on the growth rate of fishes is 0.5. This implies that genetic differences account for half of the individuals' growth rates (Gjedrem, 2000).

Selection: Specific individuals were selected for breeding based on the desired traits. For example, selection may be made to use fast-growing parent fish or disease-resistant parents (Nguyen, 2016).

2.1. Breeding Strategies

a) Inbreeding: Breeding closely related individuals together, particularly to maintain and improve desirable traits and remove undesirable traits from stock, can also lead to a rise of inbreeding depression, whereby the progeny lose their fitness due to the expression of harmful recessive alleles (Falconer, 1996).

b) Outbreeding: It is the process by which gametes are transferred from one genetically distinct individual to another. Outbreeding generally has the benefit of increasing phenotypic heterogeneity within a group. This raises the possibility of survival and evolutionary change and often allows individuals to adapt to a greater range of environmental situations (Woodruff, 2001).

c) Hybridization: Breeding genetically distinct individuals or groups to create hybrids individuals with new traits e.g. faster growing or better resistant to diseases (Rahman *et al.,* 2018).

3. Genetic Assessment and Evaluation

Phenotypic Evaluation: Determining parameters like the growth rate, feed efficiency ratio, disease resistance, or breeding performance. For example, the growth rate may be calculated by weighing fish after regular intervals, whereas to study disease resistance, such as using challenges with specific pathogens and then looking at the percentage of fish that survive (Kashyap *et al.*, 2024; NRC, 2012).

Genotypic Evaluation: It focuses on the genetic makeup of individuals, DNA sequencing and molecular markers are used to estimate genetic variability as well as to identify important alleles. This increases the ability of breeders to make better choices since it is possible to trace beneficial genetic variations associated with traits such as improved growth or disease resistance. This makes it possible to appreciate the genetic resources available in aquaculture species enhancing breeding accuracy (Puthumana *et al.*, 2024).

Genetic Parameter: Estimate genetically correlated and heritable between the traits. Statistical tools like animal models are available for estimating heritability, while the estimation of genetic correlations involves evaluating the behavior of various traits (Kashyap *et al.*, 2024; Du *et al.*, 2021).

4. Breeding Technologies

Selective Breeding: Selection of individuals from a population with favorable traits for propagation and improvement of those traits in their offspring. This procedure includes selecting fish with desired characteristics, for example, larger body size or breeding performance so that these characteristics are retained in the next generations. Selective breeding has worked very well towards enhancing growth rates and general productivity in important fish farming species like salmon (FAO, 2024).

Crossbreeding: The process of breeding two distinct breeds from the same species to produce a new breed. A typical example is where fast-growing species may be bred with one that is resistant to diseases to develop offspring with both traits. As it has been very useful in the advancement of bred fishes, this approach is exacted more often in the production of hybrid species, which are known to perform better than the parental lines (Huang *et al.*, 2023).

Genetic Engineering: The direct use of biotechnology to alter an organism's genome. It is a collection of technologies that alter cells' genetic composition, including transferring genes both within and between species to create new or improved organisms (Puthumana *et al.*, 2024).

5. Success of Selective Breeding in Major Aquaculture Species

Selective breeding programs in the Atlantic salmon (*Salmo salar*) have formed the basis of aquaculture development, especially in Norway where efforts at breeding fish began in the 1970s. The programs have improved several important traits, for example, growth rate, resistance to diseases and delayed sexual maturation. Perhaps the most important has been the increase in resistance to infectious pancreatic necrosis (IPN), a viral disease that poses a threat to farmed salmon. The Norwegian program is the best selective breeding program in the world in demonstrating the efficiency of family-based selection as several traits are being improved at the same time (Kashyap *et al.*, 2024; Du *et al.*, 2021). Another species is Nile tilapia (*Oreochromis niloticus*), which is considered one of the top-farmed species in the world. Therefore, the Genetically Developed Farmed Tilapia (GIFT) project has played a significant role in aquaculture. GIFT started in the 1980s and this program has raised the growth rate of tilapia strains to 60-80% compared to base populations. GIFT has made tilapia to be bred in culture systems, especially for developing countries. In recent years, selective breeding efforts have also been focused on improving the health of fish, especially against bacterial pathogens like *Streptococcus* spp. which are known to be present in tilapia economies.

Just like salmon and tilapia, selective breeding in carp, particularly the Indian major carp such as rohu (*Labeo rohita*) has proven to be successful. In India, selective breeding of the rohu has resulted in an increased growth rate of the fish by 17% for several generations of the breeding program. Considering that carp is the most commonly cultured species in aquaculture in Asia, other breeding improvement programs have been designed not only to increase growth but also to focus on resistance to diseases. Indian aquaculture is largely dominated by catla (*Catla catla*) and mrigal (*Cirrhinus mrigala*) species and has greatly benefited from these schemes. In addition, common carp (*Cyprinus carpio*) improvement programs have facilitated advancements in both growth performance and disease resistance over time (Kashyap *et al.*, 2024; Du *et al.*, 2021).

6. Challenges and Limitations in Genetic Improvement

Aquaculture has a range of economically important traits, such as resistance to diseases and growth, which are genetically complex. These traits are commonly known to be polygenic *i.e.* several genes are responsible for each of these traits contributing to the phenotype. This further complicates the selection process as one cannot easily isolate those genes that are responsible for these traits and select them. In addition, the interaction between genes, as well as with the environment, makes breeding more difficult. Therefore, accurate improvements in performance due to the selection of polygenic traits require comprehensive strategies that utilize more effective methods like intensive use of marker-assisted selection (MAS) and genomic selections (Kashyap *et al.*, 2024).

Aquaculture productivity improvement through genetic improvement also has environmental implications which are of great concern. Genetically modified organisms released in their natural habitat can endanger the habitat's biota due to genetic intermix. There could be a resulting low in genetic variation as well as a shift in the balance between wild and cultured species for such resources. There are also environmental impacts associated with aquaculture such as eutrophication, pathogen spread and removal of the natural environment which all need very effective monitoring and management practices (FAO, 2019). Lastly, another issue that limits the progress of breeding of improving aquaculture is the data gap. Lack of complete information on phenotypic and genetic data during the breeding program of many species restricts the accurate predictions of the selection of desirable traits. To establish effective breeding programs, there will need to be extensive data, which includes the heritability of the trait, genetic correlations and environmental aspects (Du *et al.*, 2021). Therefore, genetic improvement programs highly rely on the collection and analysis of the relevant data.

7. Future of Genetic Improvement in Breeding for Aquaculture

Genomic approaches such as marker-assisted selection (MAS) and genomic editing are transforming the breeding of fish and shellfish in aquaculture. The application of these molecular methods enables breeders to search out and find genetic markers that are associated with important economic traits such as growth, feed efficiency, reproduction and disease resistance (Du *et al.*, 2021). So, by including these markers in the breeding program, the breeders are enabled to increase both the accuracy and speed of the process of selection and help in reducing the time of phenotypic evaluation.

In particular, genomic selection is useful in that it employs genome-wide information, enabling multi-trait selection at once. Although genome editing technologies such as CRISPR/Cas9 have many potential applications in aquaculture, a progressive change in aquaculture can occur as a result of the increasing use of genome editing techniques for genetic improvements in cultivated species. CRISPR modifies particular genes associated with those growth rates, reproduction cycle, disease resistance as well as tolerance to climatic change (Kashyap *et al.*, 2024). This technique also helps to improve those traits that have been previously difficult to attain through traditional selective breeding practices. The only drawback is that there are still some issues to address, including regulators and the perception of GMOs by the public as a whole. This is, however, likely to delay the acceptance of genome editing technologies in aquaculture regardless of their potential (Puthumana *et al.*, 2024). Do not engage in breeding in excess - these are the basic considered rules of productive cultivation of aquatic animals. However, the development of sustainable principles has to be a deciding factor in designing future breeding schemes. As aquaculture continues to grow, it becomes vital that genetic advances do not contribute to environmental destruction. To address emerging issues due to the rise in aquaculture, breeding programs need to widen their scope to include factors that relate not just to the production of fish but also to the biosafety and environmental impacts of aquaculture. For example: the use of wild fish as feed; the impacts of farmed genetically improved species on the local ecosystems, *etc.* The problem of genetic and ecological interactions will also be an important aspect of aquaculture sustainability in the future. It will be necessary to ensure that the cultured species do not adversely impact the natural populations of those species due to either inter-specific competition or genetic introgression (FAO, 2019; Du *et al.*, 2021).

8. Conclusion

Breeding through genetic improvement has a lot of potential to improve the production of aquaculture and its practice. Using advanced breeding techniques and genetic data, an aquaculturist can improve existing fish strains and also create better fish strains for aquaculture which leads to improved production, cost efficiency and quality of products. However, the introduction of genetic improvement breeding programs implies proper planning and design, effective genetic assessment and a focus on genetic diversity within the populations. As the aquaculture sector continues growing, genetic improvement breeding practices play an important role in ensuring the maintenance of a sustainable and profitable future.

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