Selective breeding in aquaculture: Current state of knowledge and applications

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Introduction

Aquaculture, which involves the cultivation of aquatic organisms in controlled environments, has become a crucial sector of food production [1]. This is particularly important due to concerns about the sustainability of ocean's fisheries, which are struggling to meet the increasing global demand for seafood [2]. Selective breeding has been a powerful tool in improving agricultural and livestock production for decades. The practice of selective breeding dates back to the experiments of Gregor Mendel, in the 19th century [3]. However, the adoption of selective breeding in aquaculture has been slower compared to its application in plant and terrestrial animal production [4].

Starting as early as 1919 with the work of Embody and Hyford selecting for increased survival to furunculosis in brook trout [5], and then in 1920 with the development of productive strains in common carp [6], these experiments paved the way for further research in selective breeding for desirable traits. Throughout the years, a range of selection experiments have been conducted to improve the genetic characteristics of different fish species. These studies aimed to enhance traits that are economically important in aquaculture, such as growth rate and disease resistance etc. The mentioned studies, conducted by researchers like Argue *et al.* [7]; Dunham [8]; Gitterle *et al.* [9]; Hetzel *et al.* [10]; Hussain *et al.* [11] and Langdon *et al.* [12], contributed to the knowledge surrounding selective breeding in aquaculture.

According to Mair [13] less than 20% or even less than 10%, according to Gjedrem [14] of world's aquaculture production comes from genetically improved stocks. This suggests that the majority of aquaculture production still relies on non-genetically improved populations. The reasons for this situation include insufficient information available about the reproductive cycles of many cultivated species [15]. Understanding the reproductive biology and behavior of these species is crucial for implementing effective genetic improvement programs. Many aquaculture programs still rely on capturing wild specimens for breeding purposes. This practice can hinder the domestication of the species and reliance on wild-caught individuals can introduce genetic variability that is not aligned with the goals of breeding programs. The lack of knowledge about quantitative genetics, breeding theories, and breeding programs is another hurdle. For successful genetic improvement, researchers, extensionists, and fish farmers need to understand the principles of genetics that govern traits of interest. This knowledge gap can impede the development and implementation of effective breeding strategies.

By repeatedly selecting and breeding individuals with the desired characteristics, the frequency of those traits in the population increases over time. This approach is highly effective for improving traits like growth rate, disease resistance, and product quality [16]. Unlike some other genetic approaches (Figure 1) like hybridizations and cross-breeding, chromosome manipulation, sex control and transgenesis; the genetic improvements achieved through selective breeding can be passed down to subsequent generations without the need for continuous intervention. Selective breeding offers the advantage of scalability.

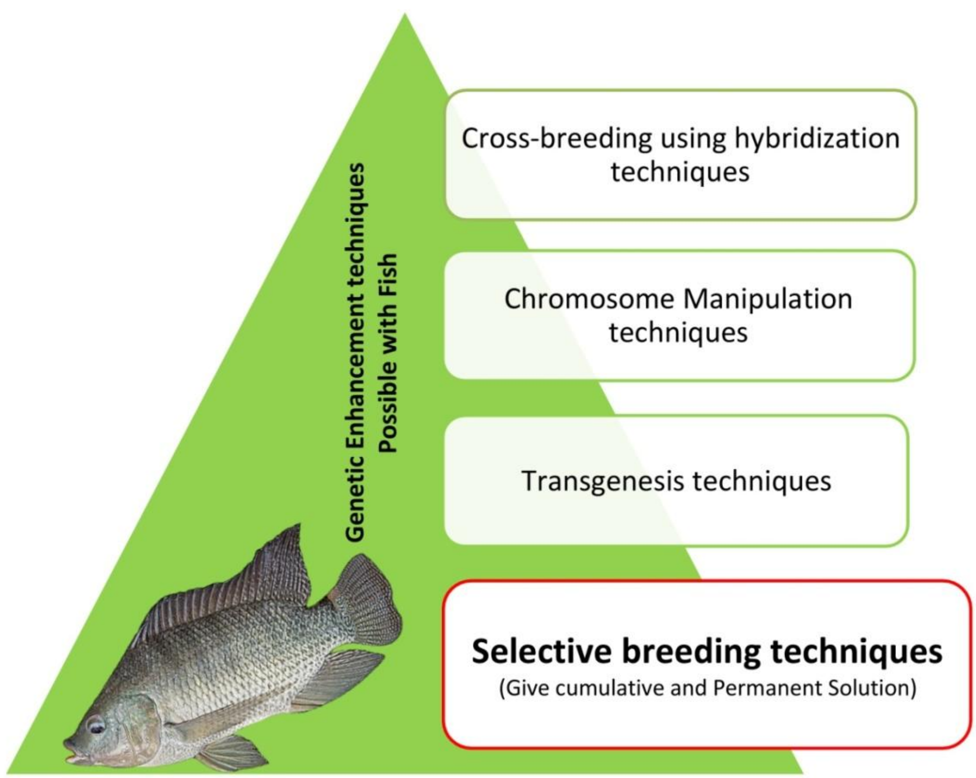

Figure 1: Breeding techniques in aquaculture

Thus, selective breeding is a cornerstone of genetic improvement in aquaculture. Its ability to achieve permanent, heritable gains in traits, its scalability, and its potential to reduce production costs and improve product quality make it an invaluable tool in the development of efficient and sustainable fish farming practices. Therefore, this book chapter aims to give some overview of selective breeding, certain breeding programs and its current status, outcomes of selective breeding in aquaculture species and its application to encompass the increasing demand of sourced proteins i.e., proteins from fishes for increasing human population.

Selective breeding programs and current status in aquaculture

Several research studies have consolidated details related to the layout of aquatic species breeding schemes [17] and breeding strategies [15]. Initially, breeding programs employed the words individual selection and mass selection, regularly used interchangeably. These terms refer to selection methods based solely on an individual's phenotype and common strategy practiced in fish breeding due to its simplicity. This method doesn't require individual identification or the maintenance of pedigree records and leads to rapid improvement. However, there are potential risks associated with mass selection, particularly the risk of inbreeding. Inbreeding can occur when the best offspring are consistently chosen from a small number of parents, especially if the progeny groups are large. This process can lead to a reduction in genetic diversity within the population, which can negatively impact the overall health and performance of the aquatic species being bred. An example is provided using *Nile Tilapia* (*Oreochromis niloticus*), where two generations of mass selection for growth rate showed no improvement over the original base population [18]. The lack of response to selection in his case was attributed to factors such as inbreeding and genetic drift, highlighting the potential limitations of simple and unstructured mass selection methods. To mitigate these issues, it is suggested that a larger number of parents be used in the breeding program, as indicated by studies by Gjerde *et al.* [19] and Villanueva *et al.* [20]. Structured breeding plans and more sophisticated selection strategies may be necessary to achieve significant and sustained improvements in aquatic species while minimizing the risks associated with inbreeding and genetic drift.

Another breeding programs use the within-family selection in improving *Tilapia* strain in SE Asian countries through selective breeding. The study was conducted by Uraiwan and Doyle in 1986 [21]. The selection program was carried out at the Freshwater Aquaculture Center (FAC) of Central Luzon State University in the Philippines. The basis for selection was the body weight of *Tilapia* at 16 weeks of age. The selection line began with a base population that consisted of four strains of *Tilapia*. Nineteen full-sib (siblings with the same parents) groups were established. To prevent inbreeding, the heaviest male from one family was mated with the two heaviest females from another family. After 12 generations of within-family selection, the genetic gain in body weight was estimated to be 12.4% per generation. This indicates a consistent improvement in body weight across generations. The study suggests that the selective breeding program resulted in a strain of Tilapia with improved performance characteristics. According to Camacho *et al.* [22], within-family selection was found to be easy to manage and rotational mating effectively addressed concerns related to inbreeding.

The combined selection refers to a breeding strategy that takes into account both individual performance data and the genetic information of related animals (such as full siblings, half-siblings, and progeny) to improve the accuracy of estimating the breeding values of individuals. This approach is valuable because it increases the accuracy of predicting an individual's breeding value, which is a key factor in selecting the best candidates for breeding programs. In the earlier work with fish mentioned [23], selection index theory was used to combine individual, full-sib, and half-sib information. A selection index is a mathematical tool that combines multiple sources of information, such as phenotypic data and genetic relationships, to predict the breeding value of an individual. However, while selection index theory can be effective, it has certain limitations that were addressed through the development of more advanced methodologies like Best Linear Unbiased Prediction (BLUP) [24]. One significant advantage of BLUP procedures is that they allow for the estimation of g enetic gain by examining the mean of the estimated breeding values (EBVs) in each generation or year of selection. The availability of computer programs, such as PEST [25] and ASReml [26] has greatly facilitated the implementation of BLUP procedures. These software tools can handle large amounts of pedigree and phenotypic data, allowing for more accurate estimation of breeding values and better-informed selection decisions.

Several studies documented successful application of combined selection for fish improvement in developing countries. Such as:

1. The GIFT Project (Genetically Improved Farmed Tilapia) in Philippines:

- ✓ Species: *Nile Tilapia* (*Oreochromis niloticus*)
- ✓ Genetic Gains: Reported genetic gains of 12-17% per generation over five generations.
- ✓ Focus: The main focus of selection was growth rate.
- ✓ Reference: Eknath *et al.,* 1998 [23].

2. The *Jayanti Rohu* Selective Breeding Project – India:

- ✓ Species: *Jayanti Rohu* (*Labeo rohita*)
- ✓ Genetic Gains: Reported a genetic gain of 17% per generation over five generations.
- ✓ Focus: The primary emphasis was on improving growth rate.
- ✓ Reference: Reddy *et al.,* 1999 [27]; Mahapatra, 2004 [28].

3. The *Oreochromis shiranus* Selection Project - Malawi:

- ✓ Species: *Malawian indigenous Tilapia* (*Oreochromis shiranus*)
- ✓ Genetic Gains: An accumulated gain of 13% over two generations.
- ✓ Focus: The selection project aimed to improve growth rates in this indigenous Tilapia species.
- ✓ Reference: Maluwa and Gjerde, 2007 [29].

Massive family-centered breeding programs, currently developed as the industry standard for the genetic advancement of aquaculture species, were first introduced for *salmonids* in the 1970s [30], *Nile tilapia* in 1988 [31], and marine prawn *P. vannamei* in 1993 [32]. After that, selection programs based on sib data have been utilized for a variety of species of aquaculture throughout the globe.

While there is significant potential for achieving high genetic gains in aquatic species through breeding programs, the development and implementation of these programs have been slow. A survey from 2003 (cited by Gjedrem and Baranski in 2009) indicated that there were only 60 family-based breeding programs in aquaculture, covering less than 5% of global aquaculture production at that time [33]. More recent surveys by Neira [34] and Rye *et al.* [35] suggest that the number of family-based selection programs in aquaculture has increased, surpassing 100 programs. It's also noted that there might be additional programs that have not been accounted for. The survey revealed that the highest number of breeding programs were for tilapia (27), followed by Atlantic salmon (13), and rainbow trout (13). However, among the widely farmed cyprinid species, only common carp (8) and rohu carp (1) were represented in the breeding programs. In 2010, it was estimated that around 8.2% of aquaculture production was based on genetically improved stocks. The exception was *Atlantic salmon*, where around 97% of the world's production used improved stock [33]. Considering potential gaps in the data, it's suggested that less than 10% of the global aquaculture production in 2010 was based on genetically improved stocks. The estimate might be optimistic, as some breeding programs could have been overlooked, and larger aquaculture companies might be implementing in-house selection programs that were not accounted for.

Outcomes of selective breeding in aquaculture species

The study by Schaperclaus in 1962 [36] from Germany demonstrated a significant selection response for reduced mortality due to furunculosis in common carp. These can be seen as one of the pioneering attempts at improving disease resistance through selective breeding in aquaculture. In 1920, researchers started developing two productive strains of common carp [37]. This marked the beginning of strain development in carp, an economically important species in aquaculture. Nemashev [38] and Kirpichnikov [39] reported that heritability estimates for weight in fingerlings of common carp show genetic influences on growth. The reported heritability values of 0.21 and 0.10 indicate that genetics play a moderate role in determining the weight of these young fish.

In *Brook Trout* (*Salvelinus fontinalis*), Embody and Hyford in 1925 selected surviving brook trout from endemic furunculosis population [40]. The Survival rate increased from 2% to 69% after three generations of selection. In *Rainbow Trout* (*Oncorhynchus mykiss*), Donaldson started breeding rainbow trout in 1932 and increased growth and fecundity was reported. Donaldson and Olson in 1955 [41] managed to develop the "Donaldson" strain of rainbow trout through directed individual selection. This strain is highly appreciated by trout culturists not only in the USA but also globally. Despite the success of this pioneering work, there was relatively little research conducted in the field of selective breeding for aquaculture species before 1970. In the mid-1960s, Moav and Wohlfarth [42] initiated a mass selection program in common carp. The primary objective of this program (started in 1965) was to improve the growth rate of the carp through selective breeding. However, despite their efforts, this program did not yield any significant improvements in the growth rate of the carp. Another breeding program initiated during the same period, with the goal of developing common carp that were resistant to dropsy, a serious infectious disease. This program was led by Kirpichnikov [43] and was conducted over the long term. The breeding strategy involved selection within local and Siberian wild carp populations from the river Amur, as well as crossbreeding between them. This selection effort proved successful, as resistance to dropsy was improved through selective breeding. As a result of this successful program, three distinct stocks of Krasnodar common carp were developed. Additionally, crossbreeding between the different stocks of Krasnodar common carp was carried out, resulting in heterotic crossbreds. These crossbreds showed a combination of the favorable traits from the parent stocks and were well-suited for commercial production. The commercial use of these heterotic crossbreds extended beyond the Krasnodar region to other parts of the former Soviet Union, indicating the broader impact and success of the breeding program in improving the characteristics of common carp for farming.

With *Atlantic Salmon* and *Rainbow Trout* in Norway, AKVAFORSK started breeding experiments in 1971, later transformed into a national breeding program. Traits considered for selection included growth rate, low frequency of early maturation, disease resistance, and flesh quality, color and fat percentages. Genetic gains of 13% for *salmon* and 14.4% for *trout* were reported by 1985. The Philippines National Tilapia Breeding Programme was started in 1993 with broodstock from the GIFT (Genetic Improvement of Farmed Tilapia) programme. This resulted in significant growth improvement in GIFT *Nile Tilapia* through selective breeding. The program achieved a growth improvement ranging from 77% to 123%, which was considered superior to the results obtained from crossbreeding experiments. The program managed to achieve an impressive 11 percent genetic gain per generation in GIFT *tilapia*. This rate of genetic improvement is noteworthy, especially when compared to genetic gains obtained in other species of fish under similar breeding programs.

Collaborative research project between CIFA (India) and Institute of Aquaculture Research, (AKVAFORSK, Norway) was initiated in 1992 for Rohu (*Labeo rohita*) improvement. The fingerlings (young fish) from different Rohu populations were brought to CIFA, where they served as the base populations for the breeding program. Over time, the researchers likely selected individuals with the most desirable traits and bred them to create successive generations of fish with improved genetic characteristics for farming. Numerous selection studies and breeding schemes intended for improving rate of growth have lately been accomplished across multiple species, leading to 10-20% gain in every generation. Table 1 lists the species and nations participating in selective breeding.

Species	Countries	Genetic Gain% per Generation	No. of generation	References
Channel Catfish (***Ictalurus punctatus***)	USA	13%	6	[8]
Coho Salmon (***Oncorhynchus kisutch)***	Chile	15%	4	[44]
Atlantic Salmon (***Salmo salar***)	Chile, Iceland, Ireland & Scotland	14%	6	[45]
Rainbow trout (***Oncorhynchus mykiss***)	Chile, France & USA	13%	2	[45, 46]
Common Carp **(*Cyprinus carpio*)**	Israel	-	-	[42]
Indian rohu carp **(*Labeo rohita*)**	India	29.6%	4	[28]
Silver barb **(*Barbodes gonionotus*)**	Bangladesh	12%	3	[11]
Tilapia **(*Oreochromis niloticus*)**	Philippines	12%	12	[47]
Tilapia **(*Oreochromis niloticus*)**	Egypt & Kenya	17%	5	[48]
Sea Bream **(*Sparus aurata*)**	Greece	22%	1	[40]
Shrimp **(*Penaeus monodon*)**	Colombia	4.2%	4-5	[9]
Oysters **(*Crassostrea gigas*)**	Asia, Europe & America	9.5%	1	[12]
Calico Scallop **(*Argopecten ventricosus*)**	Mexico	16%	1	[50]

Table 1: The selection response for growth rate in aquatic species under selective breeding

Applications of selective breeding in the aquaculture industry

The role of selective breeding in the aquaculture industry, its potential benefits and challenges associated with it, and how genetic data and manipulation techniques can be employed to improve aquaculture species has been reported. The points below discuss the applications of selective breeding in the aquaculture industry and how it can contribute to the improvement of aquatic species for better husbandry and production efficiency:

1. Selective Breeding as a Tool: Selective breeding involves the deliberate selection of individuals with desirable traits to be used as parents for the next generation, thus increasing the occurrence of those traits over time. This process is aimed at improving the genetic makeup of aquatic species for aquaculture purposes.
2. Human Intervention vs. Natural Selection: The selective breeding involves human intervention in the adaptation process, which substitutes natural selection with controlled breeding practices. This alteration of the natural evolutionary process can lead to both positive and negative outcomes for aquaculture, depending on the chosen traits.
3. Genetic Considerations and Well-Designed Programs: Incorporating genetic considerations and well-designed selective breeding programs into aquaculture efforts is suggested to increase the likelihood of success. This involves careful planning and execution of breeding strategies to achieve desired traits.
4. Academic vs. Industry Approach: While academic institutions have contributed to genetic data collection and research, incorporating selective breeding programs within the aquaculture industry could be more efficient and aligned with industry goals.
5. Adapting to Market Changes: Selective breeding is portrayed as a means to help the aquaculture industry adapt to market dynamics and evolving demands by producing improved stocks with desired traits.
6. Ongoing Evolution of Aquaculture: The aquaculture industry is still developing and evolving, and selective breeding is one of the mechanisms through which it can progress toward defined production goals.
7. Challenges and Potential: The aquaculture industry needs more genetic data for various species to formulate effective breeding programs. While some species like rainbow trout, Atlantic salmon, channel catfish, and carp have adequate genetic data for specific traits, there's a need for more comprehensive data collection for other important aquacultural species. The Norwegian Atlantic salmon industry is cited as an example of successful

industry-driven breeding programs. The aquaculture industry is becoming more competitive, requiring the development of efficient breeding programs to produce selectively bred stocks that enhance production efficiency. The advancement of genetic engineering techniques, such as chromosome manipulation and introduction of novel genes, complements selective breeding efforts and offers exciting potential for genetic improvement.

8. Dynamic Nature of Aquaculture: Selective breeding is viewed as a mechanism that allows the aquaculture industry to advance toward defined production goals and adapt to market demands and changes over time.

Overall, the points above emphasizes the importance of well-planned selective breeding programs, genetic data collection, and the potential integration of genetic engineering techniques to drive advancements in the aquaculture industry. Similar to agriculture, selective breeding is viewed as a major mechanism for advancing the aquaculture industry. As the market and industry demands evolve, selective breeding can help producers adapt to changes and achieve specific production goals.

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