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A Review on Genetic Improvement in Aquaculture through Selective Breeding

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Aquaculture is the farming of aquatic organisms such as fish, crustaceans, molluscs, and aquatic plants. Selective breeding is a key tool used in aquaculture to improve the genetic makeup of farmed species and enhance their productivity and desirable traits. This review explores the application of quantitative genetic principles in fish breeding, which has advanced more slowly compared to livestock breeding. Traditional fish breeding designs are often complicated by confounding effects, making it necessary to modify standard practices to distinguish additive, maternal, and non-additive genetic influences for effective genetic improvement. Selective breeding is essential in aquaculture, offering rapid selection responses and significant genetic gains. Despite the economic importance of traits in aquaculture species, there is limited knowledge of their phenotypic and genetic parameters due to underdeveloped breeding programs. This review highlights various selective breeding programs for key species such as salmon, trout, tilapia, and carp. Carp breeding, crucial in Indian aquaculture, has demonstrated substantial growth rate enhancements through selective breeding. The review underscores the potential of selective breeding to enhance economically significant traits in aquaculture, emphasizing the need for ongoing research and development in genetic improvement strategies.

Keywords: Aquaculture; selective breeding; genetic improvement; fishes.

1. INTRODUCTION

Aquaculture, the cultivation of aquatic organisms including fish, crustaceans, molluscs, and aquatic plants, has grown significantly as a crucial component of global food production. As natural fish stocks face overfishing and environmental pressures, aquaculture offers a sustainable alternative to meet the increasing demand for seafood. Central to the advancement of aquaculture is the genetic improvement of cultured species, which can significantly enhance productivity, resilience, and overall efficiency. Selective breeding, a cornerstone of genetic improvement, involves the deliberate selection of individuals with desirable traits for reproduction, thereby amplifying these traits in subsequent generations [1]. Most conventional fish breeding designs because confounding of various effects making it difficult to separate various sources of variances during the genetic evaluation. This is mostly because the source population was part of a breeding nucleus. Thus, it needs various modifications to the regular commercial breeding practice to separate the additive, maternal and non-additive genetic effects for genetic improvement [2]. Compared to farm animals, we can see selection response in aquaculture quickly [3]. Aquaculture species have few breeding strategies because of their frequently complex productive cycles. Therefore, the economic traits are not correctly defined and therefore this leads to inappropriate measures of genetic parameters. For the majority of the farmed species, there is a lack of knowledge regarding the phenotypic and genetic parameters of commercially significant features due to the lack of interest in developing breeding programmes in aquaculture.

Despite these successes, several challenges remain in the genetic improvement of aquaculture species. One of the primary issues is the genetic complexity of many traits of interest, which are often controlled by multiple genes and influenced by environmental factors [2,4]. Additionally, there is a need for more comprehensive genetic and phenotypic data to inform breeding decisions. This requires robust monitoring and data collection systems, as well as advanced genetic tools and technologies. Another significant challenge is the potential ecological impact of aquaculture practices. Species raised in captivity frequently escape into the wild, where they can interbreed with wild populations, potentially leading to genetic dilution and ecological disruption. This underscores the need for responsible breeding practices and effective containment strategies to minimize the environmental footprint of aquaculture operations.

This review aims to provide a comprehensive overview of genetic improvement in aquaculture through selective breeding. It will examine the principles and methodologies of selective breeding, highlight successful breeding programs for various species, and discuss the challenges and future directions in this field. By understanding the genetic basis of desirable traits and implementing effective breeding strategies, the aquaculture industry can continue to improve the sustainability and productivity of aquatic food production, ensuring a reliable food source for the growing global population.

A brief account of different breeding programmes and genetic parameters estimated are given below.

2. SELECTIVE BREEDING PROGRAMME OF SALMON

Beginning in the late 1960s, Norwegians began raising Atlantic salmon (*Salmo salar*) for food. The bulk of today's farmed fish are created through artificial selection and exhibit numerous marks of domestication [5].

In Early 1970’s, AKVAFORSK collect fish samples from 40 different rivers in Norwegian & one Swedish river & developed the first family for selective breeding programme [6]. The selection experiment of Atlantic salmon was started in 1971 after the farming began & samples were selected in 4 different river / localities in four population [7]. In Aquaculture, mostly growth is considered as the most important trait for genetic improvement [8]. Experiment started in 1949 & developed selected stock of chinook salmon & selected stock show the high growth rate, more resistant to high temperature, disease resistant, early mature & high survival rate than non-selected stock [9]. Both growth & sexual maturation is considered as a complex process & Controlled by several genes & environmental factor [10]. In selective breeding programme, the type of selection combined individual & family selection show an efficient effect [8]. The long-term selection programme on Coho salmon may produce a large genetic improvement dramatically reducing the genetic variation [11]. In the comparisons of growth rate of sibling retained under hatchery condition & those for habits in experiment stream, where the growth rate is similar for wild condition, were on fast growing genotype in the stream realized 90% for their growth [12]. Selective breeding develops resistant against sea lice by reducing the impact of sea lice in salmon. Predicting the growth at early study is negligible value for predicting at later stages in salmon [13]. The selection on juvenile’s trait may play crucial role in the evaluation of maternal traits from a natural population [14]. In indirect type of selection, standard is helpful to improve Feed Efficiency (Growth) in Aquaculture species.

3. SELECTIVE BREEDING PROGRAMME OF TROUT

After 38 years of selection in rainbow trout, males get early mature in first year (680 gm) & female are late mature in second year (4.5 kg) [15]**.** Families from the Brood stock Body weight and cortisol response to a 3-hour confinement stressor are positively correlated [16]. The image analysis to genetically improve fish flesh quality [17].

4. SELECTIVE BREEDING PROGRAMME OF TILAPIA

In the Asian subcontinent the selective breeding for Aquaculture species was started by ICLARAM (International Centre for Living Aquatic Research Management) in 1988 under auspices, the two projects the genetic improved farm tilapia & Dissemination & Evaluation of genetically improved tilapia in Asia [18]. Selective breeding of Tilapia is easy compared to other fish species because of prolific breeder. The Gift strain in 100% faster compare to their base population and is able to thrive in a wide range of environment, leading to increase in productivity & income for fish farmer thought many developing countries in Asia. Nile Tilapia was selected due to its popularity in Aquaculture, Short generation time of approximately 6 months, naturally high tolerance to variable water quality, good Disease resistance & ability to adapt much different forming system. After five generations of selection [18] reported on annual genetic improvement is 12-17%, which is higher than our estimate for ninth generation. Nevertheless, found evidence of genetic variation in the three traits studied, and the cumulative genetic gain of about 14% in harvest weight, coupled with the favourable genetic correlation of the latter trait with survival rate, augurs well for the future of the line [19]. A genetic selection program is underway in Egypt to enhance disease resistance in tilapia [20]. Bentsen [21] demonstrate the study on GIFT tilapia (*Oreochromis niloticus*) throughout five generations, the body weight of Nile tilapia from an artificial farmed population was progressively enhanced through repeated selection. This selection process involved assessing individually tagged and pedigreed individuals. The overall growth increased to a range of 67 to 88 percent. Abwao [22] presented a report on the importance of enhancing the genetic quality of *Oreochromis niloticus* through selective breeding, drawing on current and past global studies and reports. The genetic enhancement of tilapia is crucial for supplying high-quality seeds to farmers, resulting in increased body weight and the sustained expansion of aquaculture.

5. SELECTIVE BREEDING PROGRAMME OF CARP

Carp has been the backbone of the aquaculture production in India & IMC, catla rohu, mrigal & together with other exotic carp, including grass carp, common carp, silver carp all contribute over 85% of the aquaculture production of the country. Due to the three fast growing nature and good taste carp (IMC) is an important species of aquaculture scenario of Indian aquaculture. These are highly prized fishes through originally inhabitant from Ganga River in North India & the rivers of Pakistan, Bangladesh, Nepal and Burma. The Popular culture technique for carp in India is known as composite carp culture.

5.1 *Labeo rohita*

Labeo rohita (Ham. 1822) family Cyprinidae is an important group of fish & commercially culture practise throughout the world*.* *Labeo rohita* is considered as a major carp & it is a freshwater fish species found in tropical geographical areas. Due to the most preferable fish species this fish species, in selected for the selective breeding programme. In India the First selective breeding started in 1992 and the first Candidate species is *Labeo rohita* (Ham. 1822). First genetic improved variety of rohu given name is Jayanthi rohu. It has shown genetic improvement in the genetic gain of 17% generation for growth rate [23]. This species is the wide culture fish species in Asian country at the South-eastern part of Srilanka, Pakistan, India, Bangladesh etc. The Indian major carp, which are also known as the Gangetic carp, are the natural inhabitants of the Ganga River. Carp are dominant in most of the Asian countries and other countries like India, Bangladesh, Nepal, Myanmar, Thailand, Pakistan, Indonesia, China, Vietnam etc. The three IMCs, namely catla (*C. catla*), rohu (*L. rohita*) and mrigal (*C. mrigala*) contribute the bulk of production 5863263 tons [24].

5.2 Selective Breeding programme in Rohu

A selection program in the *Labeo rohita* carp for improvement growth was initiated since 1992 at the Central Institute of Freshwater Aquaculture, Kausalyaganga, Bhubaneswar India in collaboration with NOFIMA (AKVAFOSK), Norway. A Selection response of 17% high growth generation has been achieved after seventh [23]. Selective breeding has very potential for improving the genetic makeup & genetic improvement of fish in aquaculture production. Selective breeding in the aquaculture started in the 1990s and the first candidate species for selective breeding is a salmon in Norway. Selective breeding for the improved economic trait like growth rate are important traits in view of the economic Importance.

The main objective of genetic improvement programme is to increase a harvested body weight, disease resistance, feed efficacy conversion ratio through a breeding of individual, families' selection. Basic function of selective breeding, genetic change individual by changing allele frequency at loci, responsible protein traits through a selective breeding can improve genetic improvement generation to next generation. Through the high fecundity of fish, the possibility of the many samples from each single family.

Four generation of selection increases harvested body weight, direct genetic gain harvested of approximate 7% per generation. The selection did not have negative impact on survival rate over the 10-year research period. The current study confirms that substantial genetic variation exists within the Serbian carp & the results strongly indicate the potential for genetic improvement through selective breeding programme [25]. High stocking density play a crucial role for bacterial pathogenesis, though it promotes stress level in fish [26].

5.3 Selective Breeding Programme of Catla

First Selective Breeding programme for catla, in India is already started by ICAR-CIFA for the genetic improvement for selective breeding & Collect Catla nine strain from different source for estimation genetic difference. The Phenotype & microsatellite marker information used to infer relationship with & between the nine strains of catla *(Catla catla)* & this information help & to establish a base population for selective breeding [59]. The analysed molecular variance in about 58.63 %.

Table 1. Selective breeding of some aquaculture species

S.NO.	Species	Author	Country	Traits	Year	Method of selection	Remark
i.	Tilapia	Rezk et al.[16]	Malaysia	Growth rate	2009	Pedigree selection	Cumulative genetic gain of about 14% in harvested weight.
	Nile-Tilapia	Shoemaker et al. [27]	United states	Disease resistance	2017	Within Family Selection	Research suggests that *S. iniae* and *S. agalactiae* are antigenically distinct vs vaccination.
	Nile-Tilapia	Kunita et al. [28]	Brazil	Deformities character	2013	Indirect selection	The values of genetic correlations and ranking indicated a strong association between genetic traits
	Nile-Tilapia	Bentsen et al. [21]	Malaysia	Growth rate	2017	Indirect selection	The population of Nile-Tilapia resulted in considered genetic response in growth rate (in the range to 10% - 14% per generation) across a wide range of form environments during five generations.
	Tilapia	Trong et al. [29]	Israel	Growth rate	2014	Individuals’ selection	The cumulative realized selection response across three generations of selection was 8.85%.
	Tilapia	Ninh et al. [30]	Vietnam	Growth rate	2014	Family selection	The genetic gain estimated from the present population of Nile tilapia indicates that significant & sustained genetic progress in the desired direction has been achieved in harvested body weight after four generations of selection under brackish water.
i.	Atlantic salmon	Kjoglum et al. [31]	Norway	Disease resistant	2008	Pedigree selection	The weak genetic correlation indicates that it should be relatively easy to improve resistance to each of the discoveries simultaneously.
	Atlantic salmon	Mesztal et al. [32]	Canada	Preliminary Assessment of the environment	1998	Mass selection	When captive & wild smolts were analysed as are cohort, the ratio of the effective to census number of breeders was higher than that of just the breeder that prepared the wild smolts.
	Atlantic salmon	Robinson and Hoyes [33]	Norway	Disease Resistant	2008	Within family selection	The genetic response achieved under CRIT1 & CRIT4 results in improved survival to Disease challenges after 10 generations. The genetic response CRIT2 & CRIT3 increased as the generation & phenotype correlation between traits 1 & 2 increased.

S.NO.	**Species**	**Author**	**Country**	**Traits**	**Year**	**Method of selection**	**Remark**
	Atlantic salmon	Storset et al. [34]	Norway	Resistance against infection pancreatic necrosis	2007	Family selection	A)/B) group were 29.3% /66.6% &32.0%/79.0% in fresh water & sea water respectively.
	Salmon	Gunnes and Gjedrem [35]	Norway	Growth rate	1978	Family selection	The research present in this paper shows a large difference between a fish farm in the growth rate of the fish. This is mostly due to different management & especially difference in food & feeding ratios.
	Coho salmon	Hershberger et al. [36]	USA	Growth rate	1990	Family selection	This study represents>60% increase in weight in four generations.
	Coho salmon	Neira et al. Lopes [36,37]	USA	Early spawning date	2006	Family selection	After 4 generations of selection spawning date were advanced in both populations, parent estimate for harvest weight given for increase was a decrease of 13 & 15 days in the even & odd year respectively.
	Coho salmon	Sundstrom et al. [12]	Canada	Growth rate	2005	Mass selection	The present study has shown that a major shift in the early development of Coho salmon caused by genetically increased intrinsic growth rate results in a significant of effect on emergency timing, migration pattern survival growth rate of survived fish.
i.	Rohu	Das et al. [26]	India	Disease Resistant	2014	Individual selection	High stocking density play a significant predisposing factor for bacterial pathogenesis since it promotes stress in fish.
	Rohu	Sahoo et al. [38]	India	Resistance to Aeromonas hydrophila	2011	Individual selection	The first generation of resistant line showed a higher survival (56.67% over in susceptible line in the challenge test. These results show clearly the inheritance of the resistance trait in genetic lines of rohu.
v.	Atlantic cod	Delghandi et al. [39]	Norway	Simultaneous analysis	2003	Combined family & individual selection	The result presented here indicate that the GM03, GM08, GM019, GM034.GM035, etc. microsatellite

S.NO.	Species	Author	Country	Traits	Year	Method of selection	Remark
							loci may be reliable make for assessing genetic variation in Atlantic cod.
/.	Abalone	Robinsen et al. [40]	Australia	Disease resistance and growth rate	2010	Indirect selection	Our prediction for genetic response 7-13% for improved survival for a trait like disease resistance in early generation of selection.
i.	Common Carp	Dong et al. [41]	China	Growth rate	2015	Pedigree selection	Direct gain in body weight averaged 7% of the base population per generation (two) year.
	Common Carp	Ninh et al. [42]	Vietnam	survivability	2011	Family selection	This study demonstrates the application & effectiveness of molecular parentage assignment as a tool in a selective breeding programme for common carp in Vietnam.
	Common Carp	Spasic et al. [25]	Serbia	Estimate the heritability & Genetic correlation between weight, length & height	2010	Within Family selection	The heritability estimation in the first were significant different from zero, varies between 0.34 & 0.45, in second production year heritability moderate high 0.44-0.49 Genetic correlation between weight & height & between weight, were very high 0.81 & 0.01, and in second production year it varies from 0.64 & 0.74 respectively.
	Common carp	Vandeputte [43]	France	Growth rate	2003	Family & Individual selection	Although selective breeding especially for growth rate in the common carp had moderate success in the past, new methodology such as microsatellite for parentage assignment use of DH, progenies may now give the opportunity to go had to go much deep in description of the within strain genetic variation trait.
	Common carp	Kirpichnikov et al. [44]	Russia	Disease resistance	1993	Mass selection	The results of the pond test were more evident variation in resistance to disease, viably and growth rate was very high. A positive correlation between the level of resistance & the initial weight of fish was established.
i.	Rainbow trout	Henryeen et al. [45]	Denmark	Disease resistant	2005	Family selection	Results support theadditive genetic variation for resistance to ERM, RTFS, &VHS.
	Rainbow	Kause et	Norway	Genetically	2008	No Method indicated	Our results indicate that image analysis can be

S.NO.	Species	Author	Country	Traits	Year	Method of selection	Remark
	trout	al. [46]		improve flesh composition & colour in large rainbow trout			used to genetically improve fish quality. The benefit of image analysis over many other methods is that it is a cost-effective wat to access both lipid & protein percent.
	Rainbow trout	Kause et al. [47]	Finland	Growth rate	2005	Individual and family selection	Estimation of breeding valves across the generation showed the multi trait selection has produced an average of 7% genetic gain per generation in fresh & sea water grow`th of market size fish.
i.	Arctic Charr	Nilsson et al. [48]	Sweden	Growth rate	2010	Combined selection	The growth increase of 8% over a single generation for 1.5 year –old fish, male & female fish appear have responded differently to size selection across replicate selection breeding programme of around 13% in 1st generation.
x.	Asian Seabass	Robinson et al. [49]	Australia	Growth rate	2010	Within family selection	The simulation model predicts initial means response in growth rate.
	Asian seabass	Khong et al. [50]	Vietnam	Genetic Evaluation of three tait-body weight, total length, survival	2018	Pedigree selection	The weight and length of the fish increased steadily until 270 dph after which there was a rapid increase in growth rate until the harvest - the survival trait during grows out phase (105 to 360 days) 30 to 100% among 30 families & the averaging (48.1%).
x.	Pacific white shrimp	Argue et al. [51]	USA	Growth rate & Resistance to Taura syndrome virus	2002	Within family selection	TSV resistance 70% & Growth rate achieved 21% Growth compare to unselected control shrimp after 4th& 5th generation selection.
	Penaeid shrimp	Moss et al. [52]	USA	Disease resistance	2012	Family selection	Breeding programme designed to enhance TSV survival in shrimp.
i.	Red Sea Bream	Murata et al. [53]	Japan	Growth rate	1996	No Method indicated	The average realized heritability, which was determined by the average body weight of 4-year-old brood stock & body weight of 4-year-old fish weight of 4-year-old fish in growth curve of each generation was 0.33+- 0.28.

S.NO.	**Species**	**Author**	**Country**	**Traits**	**Year**	**Method of selection**	**Remark**
i.	Oyster	Calvo et al. [54]	USA	Disease resistant	2002	No Method indicated	The present study suggests that the dual disease tolerance of *H.nelsoni&P. marinus* is a possible &straightforward selective breeding approach.
	European Oyster	Lynch et al. [55]	Ireland	Disease resistant to *Bonamiaostreae*	2014	No Method indicated	The results of the study indicate that although *bonamiaostreae* is still present in European oyster, since it introduces in the 1980s it impact is much less significant than when first introduced when the parasite was introduced,and high mortality and infection level were observed.
i.	Channel catfish	Rezk et al. [56]	USA	Growth rate	2003	Individual selection	On average, there was an increase of 8.3 % in body weight per generation.
/.	Crab (*Portunus trituberculatus*)	MU et al. [57]	China	Disease resistance to *V. alginolyticus*	2012	Individual selection	There was no mortality in the control or blank group during the experiment. The cumulative survival rate of the common stock challenged with *V. alginonolyticus* (13.3 %+- 2.9%) was significantly lower than that of the screened stock (43.5 %+- 10.4%) ($p<0.05$).
/.	Red Claw Crayfish	Jones et al. [58]	Australia	Growth rate	2000	Within family selection & between family selection	Improvement in economically valuable traits of the red claws can be achieved through simple genetic selection. In a preliminary study, a 9.5% gain in growth rate was achieved within two selected generations.

5.4 Selective Breeding Programme Common Carp

Common carp is the most preferable aquaculture species in the world. Common carp is widely distributed in Asian countries and throughout the world. In Israel, selective breeding of common carp was started in 1995. The Common carp is the only species which have Distinct variation exist. Due to this characteristic, this species can be used for cross breeding & heterosis for growth was shown to be common, though not a universal phenomenon. Cross carp heterotic effects for growth & cold tolerance are in commercial culture [60]. The significant genetic variation of growth traits in this study indicates it could be implemented in the juvenile stage in selective breeding. A better knowledge of the genetic basis of production traits may help to understand the contradictory results about selective breeding that have been observed in the past, as everything indicates that there should be genetic variation for growth rate in the common carp, but selection for growth rate has never been proven to be efficient [43]. The relatively high heritability for weight, length, and survival during the six months before harvest. This indicates that selective breeding for growth and survival in common carp is expected to be successful [61], (48). In India first-time stock development for common carp was started in Karnataka by a selective breeding programme and for the selective breeding collected 6 different strains- 2 strains from local Karnataka, hungry, Indonesia & Vietnam [62,63,64]. The selection for the increased harvested body weight is a significant improvement in the growth rate of common carp [41] and alo other species like crayfish, tilapia, magur [65,66,67,68].

5.5 Selective Breeding programme Mrigal

A selective Breeding programme of Mrigal *(Cirrhinus mrigal)* was initiated by (AKVAFORSK) Institute of Aquaculture Research in Vietnam in 1996, This effort has been prepared by Dr, H B Bentsen, T Gjedrem, Dr. H B Thient & Mr. N C Don Research Institute of Aquaculture (RIA-I) [21].

6. CONCLUSION

The genetic improvement of aquaculture species through selective breeding stands as a transformative approach to enhancing the sustainability, productivity, and economic viability of the aquaculture industry. The proper selection and breeding of individuals with desirable traits, significant advancements have been made in the growth rates, disease resistance, and overall performance of key aquaculture species. These improvements not only boost the efficiency of aquaculture operations but also contribute to meeting the rising global demand for seafood. The successes of selective breeding programs, particularly in salmon and tilapia, highlight the potential of this strategy to drive substantial gains in aquaculture productivity. However, the field faces ongoing challenges, including the genetic complexity of target traits, the need for extensive genetic and phenotypic data, and the ecological risks associated with the escape of captive-bred species into the wild. Addressing these challenges requires a concerted effort to develop and implement advanced genetic tools, robust data collection systems, and responsible breeding practices.

Looking forward, continued research and innovation in selective breeding are essential to unlocking the full potential of aquaculture. By leveraging cutting-edge genetic technologies and fostering international collaboration, the aquaculture industry can achieve more precise and efficient breeding outcomes. Moreover, adopting sustainable practices and effective containment strategies will be crucial to mitigating the environmental impacts of aquaculture and ensuring the long-term health of wild populations.

DISCLAIMER

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of manuscripts.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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