International Journal of Advanced Biochemistry Research

ISSN Print: 2617-4693
ISSN Online: 2617-4707
IJABR 2024; SP-8(4): 441-447
www.biochemjournal.com
Received: 13-01-2024
Accepted: 27-02-2024

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Genetic improvement initiatives in aquaculture

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DOI: https://doi.org/10.33545/26174693.2024.v8.i4Sf.1004

Abstract

In order to bridge the widening gap between the supply and demand of food fish, more genetic research on various species of tropical fish is becoming necessary. In few cases, there is evidence of genetic degradation, although overall, the majority of aquaculture animals now in use are comparable to wild, undomesticated stocks. Given that genetic modification of fish genes is the ultimate objective of all genetic improvement programs and that it is usually believed to involve significant financial outlays, genetic intervention need to be taken into consideration as a potential future strategy. The field of aquaculture genetics research in India is very new. Initially, the creation and assessment of carp hybrids was the exclusive focus of study. It can be accomplished by a variety of techniques, including gene mapping, hybridization, selective breeding, and genetic characterization. Certain fisheries research institutes in India are participating in genetic enhancement initiatives.

Keywords: Genetic, initiatives, aquaculture, food, enhancement

Introduction

In recent decades, the global aquaculture industry has witnessed remarkable growth, emerging as a vital source of protein for a growing human population. In this context, genetic enhancement initiatives have gained prominence as a promising approach to improve the productivity, efficiency, and sustainability of aquaculture operations. By harnessing the power of selective breeding and, in some cases, genetic engineering, these initiatives aim to develop strains of aquatic species with enhanced traits such as growth rate, disease resistance, and environmental adaptability. Aquaculture is the fastest growing farmed food production sector globally (FAO 2020) [15]. Genetic advancement is one method of raising the yield of cultivated species per unit of land and water used. With wild fish stocks dwindling due to overfishing and environmental degradation, aquaculture has become increasingly important in meeting the growing demand for seafood. However, the sustainability and productivity of aquaculture operations face numerous challenges, including disease outbreaks, environmental impact, and the need for improved genetic traits to enhance growth rates and resilience. Genetic improvement allows for the breeding of disease-resistant strains, reducing the need for antibiotics and minimizing economic losses. Selective breeding can lead to the development of strains with faster growth rates, improving production efficiency and reducing the time required to reach market size.

Among the small to medium-sized enterprises in the industry, the most pervasive and enduring technical barrier to the sustainable growth of aquaculture is the absence of improved strains that are capable of producing high-quality seed (FAO 2012) [14]. Genetic improvement can contribute to more sustainable aquaculture practices by reducing the environmental footprint per unit of production. Faster-growing fish strains require less feed and produce less waste, thus minimizing the environmental impact of aquaculture operations (Gjedrem, 2000) [17]. Genetic enhancement can also be utilized to improve the nutritional quality of farmed fish, such as increasing levels of omega-3 fatty acids or other beneficial nutrients. This can lead to healthier seafood products for consumers. Climate change and other environmental factors pose challenges to aquaculture. Genetic enhancement can help develop fish strains that are more resilient to changing environmental conditions, such as increased temperatures or fluctuating water quality parameters (Houston *et al.*, 2020) [25].

Sustainability benefits of genetic enhancement in aquaculture

Disease resistance: Genetic enhancement in aquaculture plays a crucial role in improving disease resistance, thus reducing the reliance on antibiotics and chemicals for disease control. By selectively breeding disease-resistant strains, aquaculture operations can minimize the risk of disease outbreaks and decrease environmental pollution from pharmaceuticals.

Improved growth performance: Selective breeding for improved growth performance leads to faster growth rates and efficient feed conversion in farmed fish, contributing to increased productivity and reduced environmental impact. Faster-growing strains require less feed input, resulting in lower resource utilization and waste production.

Environmental sustainability: Genetic enhancement can promote environmental sustainability in aquaculture by reducing resource inputs and waste output. Strains with enhanced feed conversion efficiency and disease resistance require fewer resources and produce less waste, minimizing the environmental footprint of aquaculture operations.

Adaptation to changing environments: Genetic enhancement enables the development of aquaculture strains with increased resilience to environmental stressors, such as temperature fluctuations and disease outbreaks. By breeding for environmental adaptability, aqua culturists can future-proof their operations against the impacts of climate change and other environmental challenges.

Resilience to environmental challenges in aquaculture through genetic enhancement

Temperature Tolerance: Aquatic organisms' sensitivity to temperature fluctuations and their resilience to such changes are critical factors in aquaculture. Genetic enhancement programs focus on selecting individuals with greater temperature tolerance, allowing them to thrive in a wider range of environmental conditions.

Disease resistance: Genetic enhancement aims to develop strains with innate resistance or tolerance to common pathogens, reducing the impact of disease outbreaks and minimizing the need for chemical treatments. This enhances the overall resilience of aquaculture systems to disease-related challenges

Water quality adaptability: Selective breeding for improved tolerance to fluctuating water quality conditions is essential for maintaining stable production levels in aquaculture. Genetic enhancement programs target individuals with efficient metabolic processes and enhanced tolerance to water quality stressors, thereby promoting resilience to environmental challenges

Feed efficiency: Genetic enhancement programs aim to develop strains with improved feed conversion efficiency, reducing resource consumption and environmental impact. This promotes sustainability by minimizing feed waste and nutrient excretion in aquaculture operations

Habitat adaptation: Genetic enhancement considers the specific habitat requirements of aquaculture species and selects for strains that are well-adapted to their production environments. This ensures optimal performance and productivity while minimizing environmental stressors associated with habitat mismatches.

Resilience to climate change: Genetic enhancement incorporates traits that enhance resilience to climate change impacts, such as thermal tolerance and stress response mechanisms. By selecting for individuals with greater adaptability to changing environmental conditions, aqua culturists can mitigate the negative effects of climate change on production systems.

Case studies

Carps: Many carp species have been widely cultivated in South and Southeast Asian nations. Important species such as rohu (*Labeo rohita*) in India (Gjerde *et al*. 2002; Mahapatra *et al*. 2007) [18, 28], silver barb (*Puntius gonionotus*) in Bangladesh and Thailand (Hussain *et al*. 2002) [26], and common carps (*Cyprinus carpio*) in China, Indonesia, and Vietnam (Ninh *et al*. 2011) [33] all have been studied as part of selective breeding programmes.
Selective breeding was started in India to genetically enhance rohu (*Labeo rohita*) growth at ICAR-Central Institute of Freshwater Aquaculture (ICAR-CIFA), Bhubaneswar, Odisha, in cooperation with Institute of Aquaculture Research (AKVAFORSK), Norway in 1992. Five wild river strains and one locally farmed stock were chosen to create a base population (Reddy *et al*., 2002) [37]. Rohu was chosen as the model species for genetic selection as it exhibited slower growth in polyculture and was the most preferred by consumers among other Indian Major Carps (IMCs). Since it was the first selection work in the history of any Indian major carp, numerous processes and strategies for the program's successful implementation were standardised. The primary goals of the rohu selective breeding plan were to acquire more regarding the extent of genetic variety that is required for rohu growth and survival and to create a rohu breeding strategy based on the results attained at the centre and at other field trial units. After eight generations of selection, the improved rohu, also referred to as "Jayanti," was named in 1997 since it was formally released on Swarna Jayanti, the 50th anniversary of Indian independence. It has demonstrated a genetic gain of 18% each generation for growth traits. To promote growing genetically modified rohu "Jayanti" throughout the nation, ICAR-CIFA has organised numerous farmer-scientist meetings and awareness campaigns for hatchery owners on quality seed production. The breeding programme of rohu added disease resistance against *Aeromonas hydrophila* as a characteristic. According to Rahman *et al*. (2001) [36], haemorrhagic septicaemia, dropsy, fin and tail rot, and ulcers are all caused by the harmful rohu pathogen *Aeromonas hydrophila*. The expansion of aquaculture in India will thereby anticipate a decrease in the cost of using antibiotics or other chemical treatments as a result of the fish stock's increased disease resistance.

G3 Rohu strain: WorldFish through its Carp Genetic Improvement Program (GIP) developed stain of rohu namedgeneration-3 (G-3) Rohu in 2020 with long research from 2012; collecting wild seeds from the Halda, Jamuna, and Padma rivers at the starting. To have the brood stocks at the privately owned hatcheries level. WorldFish provided this Generation 3 (G3) rohu in 2020 and 2021 and nurseries and trial farmers to see the growth performance. It has been found that G3 rohu strain grows more than 37% faster than the conventional rohu strains now available in the country. Hatcheries, with G3 rohu brood stock first produced small scale commercially quantities of seed for sale to nurseries and farmers in 2022. Bangladesh's carp improvement programme aims to boost farm output in 2020 called G3 rohu strain. The generation-three multiplier (G3-multiplier) and control strains were spawned on the 9th of July at the WorldFish Carp Genetic Improvement Program (WFCGIP) facility, near Jashore, Bangladesh. Families contributing to the G3-multiplier and control strains were generated as part of routine genetic improvement activities. It is anticipated that improved strains would contribute to the government's goal of producing 8.6 million tonnes of fish annually by 2041.These G3-multiplier broodstock were spawned in commercial hatcheries for the first time in mid-2022. The 'G3-multiplier strain' was comprised of fish from 14 high-ranking full-sib families. The parents of these G3 families were selected on the basis of having a high estimated total additive genetic value – the sum of the estimated genetic group effect and estimated breeding value (EBV).

Tilapia: After carp, tilapia is the second most important freshwater fish. National aquaculture institutes in Asia have developed several better strains of tilapia. Fitzsimmons *et al.* (2011) [16] stated that tilapia have the potential to overtake all other aquaculture species as the most significant species worldwide. Ponzoni *et al.* (2010) [35] stated that the GIFT initiative has affected aquaculture globally. A genetically improved farmed tilapia (GIFT) strain is an example that has been the focus of significant regional and international collaborations with organisations in Malaysia, the Philippines, Norway, and the World Fish Centre. In 1988, ICLARM started the first major Nile tilapia selection programme in the Philippines. The project name was given as GIFT, or Genetically Improved Farmed Tilapia.

Early in the 1990s, the GIFT base or foundation population was established (Eknath *et al.* 1993, 2007; Bentsen *et al.* 1998) [12, 4]. These fish were selected for high growth in the Philippines for six generations prior to 1996 (Bentsen *et al.* 2012) [5]. The GIFT strain was moved to a Department of Fisheries, Malaysia, research site in 2001 and since then, the selection programme has been continuing, and by 2013, the GIFT fish had undergone 16 generations of selection ((Nguyen *et al.* 2010) [31]. The GIFT strain is better than other strains that are available in India. The primary goal of the GIFT strain's introduction is to provide high yields, quick growth, and high survival rates at a reasonable cost. Asian nations have widely used monosex GIFT strains of tilapia due to their value. According to reports, the improved kind of Nile tilapia can withstand both freshwater and saltwater without experiencing any negative effects on the fish's growth, FCR, or gill conditions. According to one study, GIFT tilapia can grow between 27 and 36% quicker than non-GIFT tilapia when mono and polyculture techniques are used. Furthermore, GIFT had survival rates 8.2–23.8% greater than local stocks. In the region, monosex (sex reversed or YY male) GIFT strain cultivation is commonly used under commercial production.

Amur Carp: Scientifically known as *Cyprinus rubrofuscus*. One of the most extensively cultivated and highly domesticated fish species in the world is the common carp (*Cyprinus carpio*). Among freshwater teleost, the largest family is Cyprinidae, which includes common carp. Since it has been farmed for approximately 4,000 years in China, several hundred years in Europe, and then throughout the rest of the world, many strains of common carp have evolved due to a variety of factors, such as geographic isolation, adaptation, the accumulation of mutations, and pressures from both natural and human selection. A long-term programme for selecting common carp resistant to dropsy, a serious infectious disease, for farming was initiated. The breeding programme consisted of selection within the local and the Siberian wild carps from the river Amur, and crossing between them. The prevailing stock of common carp has two drawbacks: it spawns in grow-out ponds before reaching commercial size (at a weight of approximately 100 g), and it sexually matures too early (less than six months). Due to competition for food, space, etc. this has led to poor growth, which has a negative impact on the production.

To solve this issue, a comprehensive review was conducted as part of the Department of International Development's (DFID) Aquaculture and Fish Genetics Research programme to evaluate the current genetic status of the common carp stocks and create strategies for stock improvement. The University of Stirling, University of Whales, UK, the former University of Agricultural Sciences, Bangalore, and the Karnataka Veterinary, Animal, and Fisheries Sciences University, Bidar, Karnataka collaborated on the programme. Originating in the Asian carp centre, the Amur wild carp expanded to the Western Asian Rivers. The Freshwater Fisheries Research Centre in Hungary provided the current Amur common carp stock of FRIC (I), Hesaraghatta for assessment and breeding purposes.

Salient features are as below

- Fast growing (~27% faster than the existing stock).
- Late maturing (First spawning at the end of first year).
- Accepts artificial feed and has similar food habit to that of existing stock.
- Not found susceptible for diseases.

Freshwater prawn: One of the most significant crustaceans in inland aquaculture in the (sub)tropics is GFP, which integrates very well with the prawn polyculture system, commonly used by Asian smallholders to raise carp or tilapia (Zimmermann *et al.* 2010) [42]. The giant freshwater prawn (GFP), *Macrobrachium rosenbergii*, was initially subjected to genetic improvement in 2007 in India following increased recognition of the benefits of producing genetically modified strains of farmed carp and tilapia. One of the most significant crustaceans in inland aquaculture in the (sub) tropics is GFP, which blends very nicely with the prawn polyculture technique commonly used by Asian smallholders to raise carp or tilapia. Again, CIFA has developed a genetically improved strain of freshwater prawn '*Macrobrachium rosenbergii'* popularly known as Scampi. Named as CIFA-GI Scampi after 14 years of generation from 2008-2022, which will enhance productivity and profitability. It has been developed as part of a collaborative endeavour of CIFA with WorldFish, Malaysia.

Scampi production in the country has experienced downfall but it has recorded a 2.5-fold increase, soaring from 8,303 tonne to 21,317 tonne in last one year (2022). According to CIFA, the multiplier hatcheries can produce around 400 million seed from the supplied brood seed.

Penaeus vannamei: Research regarding developing breeding programmes to increase disease resistance or tolerance has been sparked by the increasing impact of disease to prawn farming globally. One of the biggest obstacles to aquaculture output is disease. The key reason for the importation of *P. vannamei* into Asia has been the apparent subpar performance, poor growth rate, and vulnerability to diseases of the two main native species of cultivated prawns, *P. chinensis* in China and *P. monodon* almost everywhere else. *P. vannamei* and *P. stylirostris* do provide the Asian prawn farmer with a variety of benefits over *P. monodon,* regardless of the issues with disease spread. Genetic selection is seen to be a potential strategy in the fight against many diseases in *P. vannamei* and other shrimp species, as vaccination is not an option for shrimp and management containment techniques are typically impractical. There is evidence that prawns have successfully selected against the Taura virus and yellow Head Virus. The US Department of Agriculture (USDA) sponsored funds for the Oceanic Institute (OI) to run a selective breeding programme for Pacific white prawns from 1995 to 1998. *P. vannamei*, a specifically bred and pathogen-free (SPF) Pacific White prawn, is available in Latin America and the United States. Legally importing SPF *P. vannamei* from overseas, hatcheries in India produce seeds and sell them to farmers who cultivate shrimp by adhering to the regulations set forth by the Coastal Aquaculture Authority, a regulatory body in charge of managing the nation's shrimp industry. The majority of the prawns produced by the farmers, who cultivate them, are exported. Under the Ministry of Commerce & Industry of the Government of India, the MPEDA is the agency tasked with exporting aquaculture products, particularly prawns and catch fisheries.

Atlantic salmon: A national selective breeding program was initiated by AKVAFORSK in early 1970s by collecting fertilized eggs from Norwegian river population. By 1985 the program had been transformed into a national breeding program run by the salmon and trout producers. The goals of salmon breeding shifted from growth rate to more complicated challenges, like disease resistance, in the 1990s due to advancements in technology and the changing priorities of salmon breeders. This shift was driven by increased outbreaks of infectious pancreatic necrosis virus (IPNV), for instance. The following traits were considered for selection, body weight at marketing; Low frequency of early maturation; disease resistance, challenge test against furunculosis and flesh quality, fat %, fat distribution and flesh colour. Genetic gains of 13% for salmon and 14.4% for trout have been reported. The results show that growth of the selected fish until smolting was twice that of the wild fish. Approximately 8-10% genetic gain per generation for growth rate, age at maturation and flesh pigmentation, disease resistance was improved. The next quality trait which is likely to be included in the breeding goal is body shape. Rapid growth in Atlantic salmon is associated with deeper body shape, which is undesirable for marketing reasons since it is different from most wild fish.

Since 1960, marine ranching has dominated Iceland's production of Atlantic salmon. Initially, recaptured fish were used as broodstock in the programme, which utilised (natural) selection for return rate. From 1988 until 1993, Kollafiordur breeding facility near Reykjavik was the centre of a large-scale breeding initiative sponsored by the Nordic Council. Since 1984, a breeding plan based on Atlantic salmon caught in the St John River has been conducted in Canada by the Atlantic Salmon Federation in St Andrews, New Brunswick. The improved stocks are utilised by the salmon farming sector, and the program's design resembles to that of Norway's national breeding strategy. Early in the 1980s, imported broodstock-mostly from Norway, but also from Scotland and Newfoundland - was the backbone of the Chilean Atlantic salmon farming sector. It arrived via Australia. A breeding programme with selection based on full and half-sib data has been in place since 1996.

Rainbow Trout: Over 50 countries currently produce rainbow trout (*Onchorhyncus mykiss*), a fish that has been farmed for more than a century. Growth rate selection has proven to be quite effective; estimates of genetic gain per generation range from 10% to 13%.

Over the course of two generations, a Finland breeding programme has selected for growth rate and early sexual maturation. Selection for a higher growth rate resulted in a 7% generation response. Similar to Atlantic salmon, rainbow trout were shown to be negatively impacted by the IPN virus in some regions. Through selection, rainbow trout's resistance to IPN has significantly enhanced in Japan. According to, a very sensitive strain had an average fatal outcome of 96.1%, whereas a resistant strain had an average mortality of 4.3%.

Channel catfish

A breeding program has been developed at the USDA/ARS Catfish Genetics Research Unit at the Thad Cochran National Warmwater Aquaculture Centre in Stoneville, Mississippi (USA) to improve commercially important traits in channel catfish. It was focused on developing catfish germplasm with increased growth, feed efficiency, reproductive success, processing characteristics, and disease resistance. Generally, only 30-50% of the female broodfish spawn. Improving the reproductive efficiency to boost the percentage of female spawning is an important part of genetic improvement programme.

Oysters: Of all aquaculture species, oysters are the highest production globally, and they have a long history of being farmed in Asia, Europe, and America. The most widely farmed species is the Pacific oyster, or *Crassostrea gigas*. Selection has been done for higher live weight yield in a breeding programme on the west coast of the United States. Live weight yield is a function of both individual growth rate and survival. The yield improvements of families from selected broodstock compared to families from wild broodstock ranged from 0.4 to 25.6% in response to selection.

Within the farming conditions of Sydney rock oyster populations (*Saccostrea glomerata*) in New South Wales, Australia, a parasite known as *Marteilia sydney* commonly causes severe mortality. Following two generations of selection, the most improved breeding line had a reduction in mortality, which went from 85.7% in the control group to 63.5%. This indicates a 22% decrease in mortality following two generations of selection.

Genetic tools used for fish improvement

Gene editing technologies: Novel genome editing techniques allow for efficient and targeted improvement of aquaculture stock and might be a solution to solve challenges related to disease and environmental impacts. For a wide range of aquaculture species, innovative genetic technologies utilising DNA-based tools are being developed (Davis and Hetzel 2000). Genome editing focus on improving growth rate and disease resistance or achievement of reproductive confinement and other valued traits. Earlier they used Zn finger nucleus (ZFNs) and Transcription activator like effect or nucleases (TALENS), but most recent ones have used CRISPR/Cas 9 editor. Although ZFNs and TALENs made production of gene edited possible they proved relatively difficult to engineer and showed low specificity to target DNA sequences.

The CRISPR/Cas9 (clustered regularly interspaced short palindromic repeats/CRISPR-associated protein 9) system originally was identified in bacteria and archaea, where it provides a defence against bacteriophages and foreign DNA. The CRISPR from *Streptococcus pyogenes* and endonuclease Cas9 are introduced into a host cell with a synthetic small guide RNA (sgRNA) targeting a gene, creating a double-strand break in the DNA at a targeted site. All genome-editing tools employ site directed nuclease (SDN) technology to make a targeted DNA break. The host's non-homologous end-joining (NHEJ) or homology-directed repair (HDR) process religates the double-strand break.

Marker assisted selection (MAS)

The main idea behind gene mapping in domestic animals is the possibility of employing gene maps to locate and map the genetic loci causing genetic variation in traits with significant economic implications. It is the process of using morphological, biochemical, or DNA markers as indirect selection criteria for selecting important traits in breeding programs. It is a type of indirect method of selection of better performing breeding individuals. MAS depends on identifying the link between a genetic marker and Quantitative traits loci. This technique identifies specific DNA sequences associated with desirable traits, enhancing the accuracy and efficiency of selection processes. MAS enables the precise selection of superior individuals based on genetic predispositions, such as disease resistance, growth rate, and reproductive performance. By pinpointing beneficial genes early in the breeding program, MAS reduces generation intervals and breeding costs while accelerating genetic gain. Through targeted breeding, aquaculture industries can optimize production traits, ensure sustainability, and meet market demands more effectively, thus propelling the advancement of aquaculture towards enhanced productivity and profitability.

Quantitative trait loci (QTL) mapping: Quantitative Trait Loci (QTL) mapping in aquaculture is a sophisticated genetic technique aimed at identifying regions of the genome associated with quantitative traits of economic importance. By analyzing the inheritance patterns of phenotypic variation across populations, QTL mapping enables the detection of genomic regions influencing traits such as growth rate, disease resistance, fillet quality, and stress tolerance. Utilizing molecular markers and statistical analyses, researchers can precisely locate these QTLs on genetic maps, facilitating marker-assisted selection (MAS) strategies. QTL mapping plays a crucial role in accelerating genetic improvement programs in aquaculture by providing insights into the genetic architecture underlying complex traits, thereby guiding selective breeding efforts towards more efficient and sustainable production systems.

Environmental DNA (e-DNA) monitoring

Environmental DNA (eDNA) analysis is an emerging molecular approach for species identification from samples containing cellular DNA and extracellular DNA sloughed off all living organisms. Our ability to identify the existence and dispersion of aquatic and terrestrial organisms has been revolutionised by environmental DNA, or eDNA. According to recent data, the concentration of eDNA may also offer an inexpensive and rapid method to measure biomass and/or abundance for the purpose of assessing fishery stocks. Environmental DNA (eDNA) metabarcoding is a relatively new monitoring tool featuring in an increasing number of applications such as the facilitation of the accurate and cost-effective detection of species in environmental samples. eDNA monitoring is likely to have a major impact on the ability of salmonid aquaculture industry producers and their regulators to detect the presence and abundance of pathogens and other biological threats in the surrounding environment. eDNA analysis has been successfully employed to detect and monitor eukaryotic macro- and microbial communities and populations and is a useful tool for early monitoring systems as it allows for more accurate and standardized detection of species that are cryptic, inaccessible and of low abundance.

Challenges and considerations of genetic improvement initiatives in aquaculture

Regulatory framework: To ensure the safety, environmental sustainability, and ethical considerations were effectively addressed; the research, development, and application of genetic enhancement technologies in aquaculture require strong regulatory frameworks.

Genetic diversity: Intensive breeding initiatives designed to improve desired features may unintentionally cause cultivated populations' variation in genes to decline. This decrease in genetic variety may make aquaculture systems less resilient to change over the long term by making them more vulnerable to infections and environmental stressors.

Consumer acceptance

Demand and market acceptance for genetically modified or improved organisms can be greatly influenced by consumer views towards them. In order to increase customer trust and confidence in genetically modified aquaculture products, transparency, labelling, and education initiatives were required.

Long-term environmental impact

The introduction of creatures that have undergone genetic modification or enhancement may have unintended long-term ecological impacts, affecting biodiversity, ecosystem dynamics, and non-target species.

Intellectual property and access: Questions of equitable benefit distribution, access to genetic resources, and intellectual property rights are brought up by the commercialization of genetically modified aquaculture species. These concerns are especially relevant for small-scale farmers and developing nations.

Social and economic implications: Programmes aimed at improving genetic improvement may have an impact on market dynamics, employment trends, and the distribution of financial gains within the aquaculture industry and its supply networks.

Scientific uncertainty: Although tools for selective breeding and genetic engineering have advanced, it is still difficult to anticipate the long-term effects of genetic enhancement programmes in aquaculture due to scientific uncertainty.

Future prospects of genetic enhancement in aquaculture

- Continued innovation and refinement of genetic editing tools such as CRISPR-Cas9, TALENs, and zinc-finger nucleases for precise manipulation of fish genomes.
- Focussing more on Indian species.
- Development of climate-resilient fish strains capable of thriving in changing environmental conditions, including rising temperatures, ocean acidification, and fluctuating salinity levels.
- Engaging with consumers, fish farmers, and fishing communities to ensure transparency and accountability in genetic enhancement initiatives, promoting consumer acceptance and trust.

Conclusion

A new avenue for the development of genetic resources in aquaculture has been made possible by genetic improvement approaches. Aquaculture can benefit from the application of genetic modification technologies for a number of reasons, including increased productivity, marketability, cultural ability, and resource conservation (Customer acceptability is a significant problem. Genetic enhancement initiatives in aquaculture represent a pivotal advancement towards addressing the challenges and maximizing the opportunities within the industry. Through selective breeding, marker-assisted selection (MAS), quantitative trait loci (QTL) mapping, and environmental DNA (eDNA) monitoring, aquaculture stakeholders are empowered to expedite genetic progress, optimize production traits, and ensure long-term sustainability. These technologies enable the precise identification and manipulation of desirable genetic traits, such as disease resistance, growth performance, fillet quality, and environmental adaptability, leading to improved stock productivity and profitability. Moreover, genetic enhancement initiatives play a crucial role in mitigating environmental impacts, reducing disease outbreaks, enhancing resource utilization efficiency, and meeting the growing global demand for seafood. By leveraging cutting-edge genetic tools and scientific knowledge, aquaculture practitioners can drive innovation, enhance resilience, and contribute to the development of a more efficient and sustainable aquaculture sector, thus fostering a secure and prosperous future for the industry and its stakeholders.

Genetic enhancement initiatives represent a cornerstone of modern aquaculture practices, offering a pathway towards increased productivity, profitability, and environmental stewardship. As these technologies continue to evolve, they hold the promise of reshaping the future of aquaculture, ensuring its continued growth and contribution to meeting the nutritional needs of a growing global population.

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