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Genetically modified fish and their applications in aquaculture

Pradeepa, G[1*]., Anusuya, A.S[1]., Ajith, P[1]., Tamil Prakash, S[1]. and Somu Sunder Lingam R[2]
[1] College of Fisheries, Karnataka Veterinary, Animal and Fisheries Sciences University, Pidar, Mangalore, Karnataka, India - 575002
[2]Krishnagiri-Barur Centre for Sustainable Aquaculture, Tamil Nadu Dr. J. Jayalalithaa Fisheries University, Barur, Krishangiri, Tamil Nadu, India – 635 201
*Corresponding author maid id: pradeepagurusamy06@gmail.com
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Introduction

The cultivation of aquatic organisms, including fish, shellfish, and aquatic plants, is known as aquaculture. It includes the breeding, raising, and harvesting of these organisms in freshwater, brackish water, and saltwater habitats. At present, the industry offers a sustainable and effective means of satisfying the expanding demand for seafood at worldwide. On the other side, it provides a consistent supply of cheapest high-quality protein that promotes global food security in light of the depletion of wild fish stocks due to overfishing and environmental issues. Moreover, it contributes significantly to export revenue in many nations and plays a pivotal role in the economy by generating millions of job opportunities, particularly in rural and coastal areas. By supplementing the farmed fish as an alternative to wild catch, aquaculture also lessens the stress on natural ecosystems. Through breeding initiatives and stock improvement projects, it also aids in the conservation of endangered species.

Besides many positive approaches, the industry faces various challenges such as high vulnerability of farmed fish to disease outbreaks due to overcrowding, which results in huge economic losses and increased the use of antibiotics. The improper handling of brooders and stocking of sub-standard seed lead to slower growth, which has an impact on the profitability and efficiency of production systems. Additionally, farmed fish need more feed to grow as their feed conversion efficiency is sometimes lower than anticipated. These set drawbacks coupled with environmental issues are demanding a potential remedy to sustain the aquaculture production. In this context, development of genetically engineered fish could provide a better solution to the existing challenges in the aquaculture industry. Therefore, the present article examines the genetic modified fish and their uses, possible advantages, and related risks in aquaculture.

Genetically modified fish

Genetically modified organisms (GMOs) carry exogenous or endogenous genes and are artificially altered by directly integrating (or deleting) a single or multiple genes to introduce or modify a targeted character. In recent times, the inception of GM fish in aquaculture practices is highlighted to address the various issues such as poor growth rates, disease susceptibility, and environmental effect. Beyond commercial applications in aquaculture, GM fish offers multiple benefits in ornamental fisheries, where genetic modifications enhance aesthetic traits such as body shape, colour, fin structure, movement, *etc*.

Transgenic fish with improved features have been created using a variety of genetic engineering methods and they have resulted in higher nutritional value, disease resistance, and growth efficiency, all of which support more environmentally friendly aquaculture methods.

History and recent advancement in GM fish

The first method used for creating genetically altered fish was gene transfer, in which the novel genetic material was injected into fertilized goldfish eggs. In 1984, goldfish (*Carassius auratus*) eggs were microinjected with the recombinant plasmid Pbpvmg-6, which contained the mouse metallothionein-1 (MT-1) promoter linked to the human growth hormone (hGH) gene placed into a Pbr-bpv (bovine papilloma virus) vector. Goldfish was selected due to their resilience, ease of reproduction, and transparent embryos which makes the researchers to clearly observe the developmental processes that has been taking during the initial stages. The main goals of transgenic goldfish development were to make the strain more decorative and scientific.

In 1990s, other fish varieties like carp, tilapia, and catfish were also underwent genetic modification to enhance their growth, resilience to disease resistant, and ability to adapt to their captive environments. AquaBounty Technologies' has developed a salmon called AquAdvantage which is the first genetically engineered animal that has been authorized for human consumption in both the US and Canada. Prior to this, in 1989, Memorial University in Newfoundland, Canada, carried out the groundbreaking genetic engineering research in which the scientists microinjected a gene construct called opAFP-GHc2 into Atlantic salmon eggs to produce this transgenic animal. By fusing the Chinook salmon's growth hormone gene with regulatory sequences to the antifreeze protein gene of the ocean pout, this salmon was produced which allowed the animal to produce growth hormone all around the year instead of only during the warmer months. After 20 years of testing, the U.S. Food and Drug Administration authorized AquAdvantage salmon in 2015.

By shortening the culture duration, this salmon innovation seeks to increase aquaculture efficiency and provide a sustainable way to satisfy the rising demand for seafood around the world.

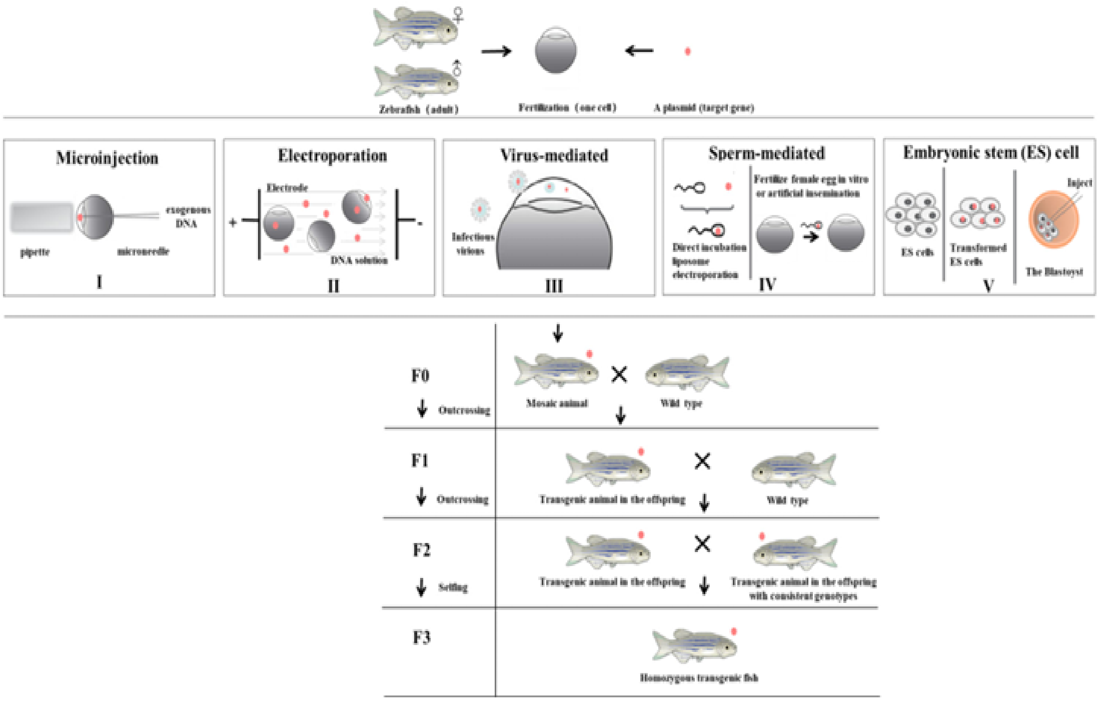

Figure 1: Production of GM fish through different gene-delivery techniques (source – Wang et al., 2021)

The most popular technique for transferring genes to create stable transgenic lines is microinjection technology (Kobayashi & Satou 2018). The other techniques include virus-mediated transfer, sperm-mediated gene transfer, electroporation technology, and transposon-mediated transfer. On the other hand, gene-editing techniques, such as zinc-finger nucleases (ZFNs), transcription activator-like effector nucleases (TALENs), clustered regularly interspaced short palindromic repeats/associated nuclease Cas9 (CRISPR/Cas9) and single-base editing (BEs), have also been used to develop genetically modified fish.

Applications of GM fish in aquaculture

Growth enhancement

Growth plays a crucial role in aquaculture as the farmer dependent on fish growth for their profit. The enhanced growth rate of fish results in increased fish production efficient farming practices, reduce the operational costs, and ensure a stable seafood supply. Faster-growing fish reach market size in a shorter crop duration which allows the farmers to produce more crop per year that leads to improved profitability.

In general, fish, that have been genetically modified (GM), is grow almost twice as quickly as traditional fish. For example, AquaBounty's Atlantic salmon utilize less feed and resources for attaining similar body weight of normal salmon. Furthermore, feed conversion efficiency can be improved through genetic engineering and selective breeding, which leads to lower feed requirement for growing the fish. On the other side, low feed requirement increases the sustainability and profitability of aquaculture. Moreover, functional analysis of GH in genetically modified fish revealed changes in immune function, swimming performance, carbohydrate metabolism, growth regulation, detoxification, transcription regulation, lipid metabolism, reproductive performance, and ability to withstand environmental stressors.

Disease resistance and health management

Aquaculture faces a significant problem with disease outbreaks, which result in high mortality rates, financial losses, and a rise in the usage of antibiotics. A potential remedy is provided by genetically modified (GM) fish, which increases disease resistance and enhance general fish health.

In this type of GM fish, certain disease or immune related genes are introduced by scientists for assisting the fish to defend the bacterial, viral, and parasite invaders. For instance, antimicrobial peptides have been added to genetically modified carp and catfish to make them resistant to common aquatic infections. This kind of genetically modified fish minimize the usage of antibiotic and reduce the risk of antibiotic-resistant strains emerging from aquatic environment. Inclusion of certain immune related genes to the genetically modified fish have improved immunological responses, which aid in their ability to combat infections and lower death rates. Overall, the GM fish withstand and grow well in sub-optimal environmental conditions, such as high salinity or low oxygen levels, which in turn improve their general health and survival rates.

GM fish in ornamental fish industry

The ornamental fish industry benefits greatly from genetically modified fish (GMF) since they are more aesthetically pleasing, more resistant to illness, and more able to adapt to a variety of conditions. In addition to improving ornamental fish's aesthetic appeal, these changes also increase their lifetime and care ability.

GM fish improve the aesthetic nature of ornamental fish by adding the bioluminescence and vivid hues in their genome. For instance, DNA from jellyfish and coral are used to genetically modify GloFish (zebrafish, tetras, and barbs) so that their aesthetic nature can be changed from light into bright hues. Similar to food fish, ornamental fish disease resistant can also be increased through GM fish production which reduced maintenance upkeep work by hobbyist. On the other hand, genetic alterations can easily adept them into home aquariums conditions more easily by enabling ornamental fish to thrive in a greater variety of water types. Moreover, the genetic modification of ornamental fish enables precise and controlled enhancements without adverse side effects in a quicker production time as compared to the traditional selective breeding methods.

Nutritional value enhancement

In general, the fish is considered as cheapest source of vital nutrients in human diet. Fish contains easily digestible protein, good fats, essential amino acids and poly unsaturated fatty acids which are vital for the balanced diet of every human life. On the other hand, there is a debate on nutritional quality of farmed fish as they are raised using feed additives, hormones and antibiotics which in turn questioning their final quality. To address this issue, GM fish can be effectively utilized in farming conditions.

Enhancing the nutritional value of genetically modified fish (GMF) is crucial for promoting human health, ensuring food security, and improving the sustainability of aquaculture systems. By genetically modifying the fish, scientists can boost the levels of essential nutrients such as proteins, vitamins, minerals, and omega-3 fatty acids. These improvements make farmed fish healthier and more beneficial to consumers.

Advantages of GM fish

In aquaculture, genetically modified (GM) fish are drawing interest as a possible remedy for issues like disease resistance, environmental sustainability, and food security. Aspects of GM fish in aquaculture for the future include the following:

1. **Higher growth rate**– Genetically modified fish can grow almost twice as fast as normal fish, reducing production time and costs.
2. **Resistance to disease and parasites** – GM fish with disease-resistant varieties require fewer antibiotics and pesticides, improving fish health and sustainability.
3. **Increased nutritiousness** – Scientists have developed GM fish with higher omega-3 fatty acids, enhancing their nutritional value for human consumption.
4. **Enhanced environmental sustainability** – Faster-growing GM fish require less fishmeal and fish oil, reducing pressure on wild fish stocks.
5. **Resilience to climate change** – GM fish have been engineered to tolerate low oxygen levels, making them more adaptable to changing environmental conditions.
6. **Ecological safety and biocontainment** –Through this technology sterile GM produced to prevent interbreeding with wild populations and minimize ecological risks.

Conclusion

Genetically modified (GM) fish represent a transformative innovation in aquaculture, bridging the gap between sustainability, food security, and scientific progress. By accelerating growth rates and enhancing disease resistance, GM fish can

Sl. No	Fish Species	Genetic Modification method	Gene Transferred / Altered	Benefits
1.	Atlantic Salmon (*Salmo salar*)	Microinjection (Transgenesis)	Growth hormone gene + antifreeze promoter	Higer growth and reduced wild stocks reliance
2.	Nile Tilapia (*Oreochromis niloticus*)	Selective Breeding / CRISPR (Recent)	Muscle growth-related genes	Better feed efficiency and nutrition
3.	Common Carp (*Cyprinus carpio*)	Microinjection (Transgenesis)	Omega-3 biosynthesis genes	Enhanced nutritional value for human consumption
4.	Channel Catfish (*Ictalurus punctatus*)	Microinjection/ Electroporation	Cecropin B gene; genes for plant-based feed digestion	Better survival in farming conditions
5.	Zebrafish (*Danio rerio*)	Microinjection/ CRISPR (Research)	Fluorescent protein genes; vitamin D, iron, zinc genes	As a research model; and to improve its ornamental value
6.	Medaka (*Oryzias latipes*)	Microinjection (Transgenesis)	Cecropin B gene; fluorescent protein genes	Elevated antibacterial activity and bright coloration
7.	Rainbow Trout (*Oncorhynchus mykiss*)	Microinjection (Transgenesis)	Cecropin B gene	Resistance to *Aeromonas*, IHNV, *Ceratomyxa*
8.	Black Tetra (*Gymnocorymbus ternetzi*)	Microinjection (Transgenesis)	Color-related transgenes	Colour improved to increase its market value
9.	Tiger Barb (*Puntius tetrazona*)	Microinjection (Transgenesis)	Pigmentation genes	Brighter appearance and market appeal
10.	Rainbow Shark (*Epalzeorhynchos frenatum*)	Microinjection (Transgenesis)	Color-enhancing genes	For better ornamental value

Table 1 – Details of GM fish with their genetic modification and benefits

significantly reduce the environmental footprint of fish farming, minimizing the need for wild-caught feed sources and decreasing reliance on antibiotics and pesticides. This not only ensures better fish health but also reduces contamination in aquatic ecosystems.

From a human health perspective, advancements in genetic engineering allow for the enhancement of essential nutrients, such as omega-3 fatty acids, addressing global dietary deficiencies. Additionally, GM fish that can adapt to climate change-induced water conditions ensures long-term food stability in a rapidly changing environment. Looking ahead, precision gene-editing techniques like CRISPR could enable even more targeted modifications, ensuring safety, efficiency, and ethical production. While regulatory frameworks and public acceptance remain key challenges in dissemination of GM fish in aquaculture industry. However, the potential of GM fish to revolutionize sustainable aquaculture and global nutrition is undeniable. By integrating biotechnology with responsible farming practices, GM fish could redefine the future of seafood industry and ensure resilience, efficiency, and enhanced health benefits for both humans and aquatic life.

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