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# Revolutionizing Fish Biotechnology: A Current Status and Future Prospects

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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

Fish biotechnology has witnessed significant advancements in recent years, driven by a convergence of interdisciplinary research efforts spanning genetics, genomics, aquaculture, and molecular biology. This synthesis study examines the significant advancements in fish biotechnology and presents potential opportunities for transforming the sector in the future. The emergence of genome editing technologies, such as CRISPR-Cas9, has fundamentally transformed the accurate manipulation of fish genomes, allowing for specific alterations in features that span from disease resistance to growth improvement. These methods show great potential for promoting sustainable aquaculture operations and protecting endangered species. In addition, the incorporation of omics technologies, like as genomics, transcriptomics, and proteomics, has yielded unparalleled understanding of the molecular pathways that underlie complex features in fish. This

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comprehensive approach has enabled the identification of crucial genes and regulatory circuits that control different physiological processes, therefore aiding the creation of new therapies for disease management and selective breeding. The recent advancements in fish biotechnology have had a significant and positive effect on the industry. These achievements highlight the potential for transforming the sector through collaboration across many disciplines, technical innovation, and the adoption of sustainable methods.

*Keywords: Fish; biotechnology; aquaculture; nano-biotechnology; crispr cas-19; genomics; crucial genes; fish biotechnology; sustainable aquaculture.*

## 1. INTRODUCTION

Biotechnology has been an innovation in several sectors, boosting sustainability efforts and transforming production methods. We have developed sustainable solutions, increased efficiency, and decreased environmental impact through the integration of biotechnological developments in industrial applications. The production of biofuels is one of the most important areas where biotechnology has made a revolutionary influence. A recent study by Panday *et al*. [1] shown that renewable feedstocks including plant biomass and algae can be efficiently converted into biofuels by genetically engineering microorganisms like yeast and bacteria. Patel *et al*. [2] found that this method reduces reliance on non-renewable resources and emissions of greenhouse gases, making it a sustainable substitute for fossil fuels.

Biotechnology is the study and practice of using biological principles to solve problems and make new goods. Although genetic engineering is the main focus, this area covers a wide range of methods and approaches. The fast-paced and ever-changing domains of biotechnology and bioengineering have brought about revolutionary changes in many areas, including healthcare, industry, and environmental sustainability. The ability to shape the future of science and technology has been unleashed by the continual surge of invention in these areas, which has spurred ground breaking achievements. This all-inclusive review article delves into the revolutionary possibilities of different branches of biotechnology and bioengineering, such as genetic engineering, bio-processing, bioinformatics, synthetic biology, bioengineering human organs, bioremediation, industrial applications, bio-inspired engineering, and emerging therapeutic modalities [3].

Revolutionary CRISPR technology and other genetic engineering advancements have made efficient and accurate genome editing possible [4,5]. The new possibilities for genetic material alteration have emerged, paving the way for developments in many other areas, including biotechnology, agriculture, and medicine. The capacity to precisely alter DNA has enormous promise for the future of medicine, including the treatment of hereditary diseases, the creation of new treatments, and the enhancement of agricultural yields. The manufacture of medications, biofuels, and other important compounds has been revolutionized by bioprocessing advances, which have provided fresh methodologies for efficient biomolecule production [6,7]. Bioprocessing has been radically altered by metabolic engineering and synthetic biology techniques, which have made it possible to optimize metabolic pathways and microbial hosts for increased production efficiency, yield, and product quality. To decipher genomes and analyze massive amounts of biological data, bioinformatics and big data analytics are now indispensable [8,9].

## 2. HISTORICAL OVERVIEW OF BIOTECHNOLOGY

Biotechnology is a fascinating field that merges biology with scientific methods and technology.

**Ancient biotechnology (Pre-1800):** Early applications and speculation.

**Classical biotechnology (1800–1950):** Significant advances in the basic understanding of genetics .

**Modern biotechnology (1950 onward):** Discovery of DNA, Recombinant DNA technology, genetically modified organisms, animal cloning, and stem cell research.

**1. Pre-18th Century:** During ancient times, humans explored ways to make food available and accessible by growing crops near their shelters. The domestication of wild animals led to animal breeding and the evolution of farming.

Notable inventions included food preservation methods, cheese, and curd. Yeast was exploited for making bread, vinegar, and alcoholic beverages like wine and beer.

**2. 18th Century (Classical Biotechnology):** Scientific evidence started emerging during this period. Observations laid the groundwork for future developments.

**3. 19th Century:** 1859: Gregor Mendel conducted experiments on pea plants, establishing the principles of inheritance. Mendel became known as the "Father of Genetics." His work highlighted dominant and recessive traits and independent assortment. Biotechnology has come a long way, from ancient cheese-making to unraveling the secrets of DNA. Its boundless potential continues to benefit every aspect of human life!

## 3. BIOTECHNOLOGY IN AQUACULTURE

**Biotechnology in Fish Feed:** Presently, fish meal is the go-to for protein in many fish diets. The rich protein and high quality of fish meal make it an ideal by-product of the fish processing industry. Having said that, there are a few drawbacks. The high price tag of roughly N520,000.00/ton is a major drawback for fish farmers. Unfortunately, global fish stocks are in decline, and fish meal is derived from the waste products of wild fish. Problems with the environment arise from aquaculture's use of fish meal. Optimal growth in fish is not possible with the levels of phosphorus it contains. Problems like eutrophication and excessive algae development result from the excess phosphorus going into the water. Scientists are employing biotechnology to create new plant-based protein sources in response to these issues with fish meal [10]. According to Danish et al. [11], plant protein may be able to help with the issue of phosphorus contamination.

**Biotechnology in Fish Health:** Polymerase chain reaction (PCR) and gene probes, two biotechnological instruments, are demonstrating promising results in this field. The development of gene probes and PCR-based diagnostic tools for several fish and shrimp infections has been remarkable. Fin fish farming has led to the development of several vaccines that protect against various viruses and bacteria [12]. Improvements in fish health are being made possible by genetic biotechnologies, which include molecular analysis of pathogens for classification and diagnosis, as well as conventional selection for disease resistance. Methods based on DNA sequence analysis are currently in use for the purpose of pathogen species and strain characterization. Finding out where the disease came from, for instance, might be possible through genetic characterization. Two strains of crayfish plague fungus were identified in Sweden using DNA analysis. One strain originated from the native species, while the other strain was found in Turkey (FAO/NACA/CSIRO/ACIAR/DFID 1999). Once the pathogen has been defined, DNA probes can be created to detect specific infections in sampled water, soil, or even entire animals. Subasinghe [13] reported the widespread use of these methods for the detection of viral diseases in marine shrimp as well as bacterial and fungal infections in fish. Aquatic animal illness control and treatment relies on having access to sensitive, quick, and dependable diagnostic assays. There is also extensive usage of direct culture of infections. Amplification techniques such as polymerase chain reaction (PCR) and DNA-based diagnostic approaches like immunoassays have emerged as solutions to these issues [11].

**Biotechnology in Surrogate Broodstock:** The process of surrogate broodstock technology involves transferring the germ cells of donors into recipients who have been sterilized, allowing surrogate parents to produce gametes obtained from donors. Numerous reports of fruitful germ cell transfers between other species and the successful reproduction of finfish have opened up new avenues for research into these previously described limits. To begin with, surrogate broodstock technology allows for the possibility of in vivo CRISPR screens in the offspring of surrogate parents, a decrease in mosaicism, and an improvement in genome editing through the use of cultivated germ cells. In addition, the method can be used to help preserve aquatic genetic resources and breed valuable species that are hard to keep in captivity. As a third benefit, it may shorten the time it takes for genetic improvements to materialize in aquaculture breeding programs by a significant margin. Lastly, it opens up new avenues for the distribution of high-quality, genetically-targeted production animals that may have had their genomes altered [14].

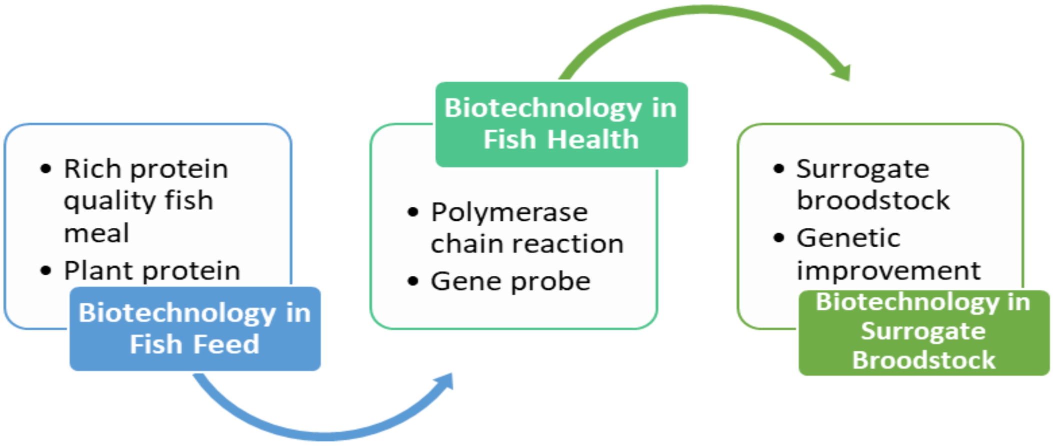


**Fig. 1. Biotechnological tools in aquaculture sector**

## 4. BIOPHARMACEUTICALS AND MEDICAL BIOTECHNOLOGY

A biopharmaceutical is a pharmacological material derived from proteins or nucleic acids that is utilized for therapeutic or in vivo diagnostic reasons. It is not extracted directly from a naturally occurring biological source. The pharmaceutical industry today occasionally uses the terms "biotechnology products," "biotechnology medicines," and "products of pharmaceutical biotechnology" interchangeably. For instance, PhRMA often includes them in its publications on the subject (PhRMA, 2001). Once again, without a formal definition, we don't yet know what kinds of compounds fall under these criteria or how they relate to the word "biopharmaceutical" [15].

### 4.1 Biopharmaceuticals

Biopharmaceuticals, commonly referred to as biologics, are pharmaceutical drugs created by biotechnology that come from biological sources. These goods may consist of materials such as carbohydrates, proteins, and nucleic acids. Recombinant human insulin (rHI) is a well-known example of a biopharmaceutical. Biopharmaceutical businesses are experts in producing these medications using biological methods [16].

### 4.2 Medical Biotechnology

Medical biotechnology is a branch of medicine that uses living cells and cell components to investigate and develop pharmaceuticals. It entails studying health and disease principles, molecular mechanisms, synthesis, purification, toxicity testing, medication delivery methods, and clinical trials. Medical biotechnology encompasses bioformulations including antibodies, nucleic acid products, and vaccinations. Advances in genomics, proteomics, and high-throughput screening have paved the door for new drug discovery methods. Biopharmaceuticals and medical biotechnology intersect to drive innovation in healthcare and improve lives [17].

## 5. AGRICULTURAL BIOTECHNOLOGY

Agricultural biotechnology also known as agritech is a fascinating field that merges scientific tools and techniques with agriculture.

### 5.1 History

Selective Breeding: For thousands of years, farmers manipulated plants and animals through selective breeding to create desired traits.

20th Century: Technological advancements led to increased agricultural biotechnology, focusing on traits like yield, pest resistance, drought resistance, and herbicide resistance.

1990: The first food product produced through biotechnology was sold. By 2003, over 7 million farmers worldwide were utilizing biotech crops, with more than 85% of them in developing countries.

### 5.2 Crop Modification Techniques

Traditional Breeding: Crossbreeding compatible species to create new varieties with desired traits. Example: The honeycrisp apple resulted from crossbreeding.

Mutagenesis: Inducing random mutations within plants using radiation or chemicals. Atomic gardens use radiation to mutate crops. Ruby red grapefruits were produced through mutagenesis.
Polyploidy: Modifying the number of chromosomes in crops to influence fertility or size. Organisms usually have two sets of chromosomes (diploidy), but this can change naturally or chemically.

### 5.3 Biofuel Production

The future's success hinges mostly on the provision of fair, reliable, environmentally-friendly, and cost-effective energy. The production of biofuel has become a prominent trend in recent years. Biofuel has the potential to serve as a viable and dependable alternative to fossil fuels. Six strains of microalgae were cultivated photosynthetically in a photobioreactor. Out of these six microalgae, the strain known as Chlorella vulgaris is the most prevalent for the purpose of producing biodiesel. Chlorella vulgaris has been utilized as a source of feedstock. The selection of species for biodiesel production can be based on the measurement of biofuel quality and lipid productivity [18].

## 6. ENVIRONMENTAL BIOTECHNOLOGY

Environmental biotechnology is a fascinating field that combines scientific knowledge with practical applications to address environmental challenges.

### 6.1 Meaning of Environmental Biotechnology

Environmental biotechnology focuses on protecting and restoring the quality of our environment. It involves using processes to detect, prevent, and remediate pollutants in the environment. By recycling biomass, minimizing waste, and adopting sustainable practices, environmental biotechnology contributes to sustainable development.

### 6.2 Objectives of Environmental Biotechnology

Optimal Resource Use: Adopt production processes that make the best use of natural resources by recycling biomass, recovering energy, and minimizing waste generation.

Bioremediation and Conservation: Promote biotechnological techniques for bioremediation of land and water, waste treatment, soil conservation, reforestation, afforestation, and land rehabilitation.

Long-Term Ecological Security: Apply biotechnological processes to protect environmental integrity and ensure long-term ecological security.

### 6.3 Environmental Biotechnology Monitoring

The primary focus of environmental monitoring is the routine measurement of a small number of specified criteria in order to draw conclusions about ecological quality. When it comes to determining how bad pollution is, there are two main approaches: physicochemical and biological [19]. There is a growing need for early-warning systems to identify toxicants at low concentrations due to the detrimental impact of these compounds on natural ecosystems [20]. We can now monitor and control at the molecular level because to the revolutionary combination of environmental biotechnology and information technology [21].

### 6.4 Bioindicators/Biomarkers

Recent environmental monitoring programs have expanded to include testing biota for contaminants and evaluating different biological and ecological responses. As a measurable response, some communities or species may alter their chemical composition or biological function in response to environmental influence. "Bioindicators" or "biomarkers" describe both the drastic shift in their environment and their reactions to it (19). You can get indications based on exposure, effect, or susceptibility. Molecular, biochemical, histo-cytopathological, physiological, and behavioral biomarkers all hold promise for biomonitoring applications. Molecular biomarkers include gene expression and DNA integrity. Biochemical biomarkers include enzymatic processes, particular proteins, or diagnostic chemicals [22].

## 7. NANOBIOTECHNOLOGY

An intriguing new area, nanobiotechnology brings together nanotechnology and biology. The biology and physics of nanomaterials make nanobiotechnology an exciting new field of study. Since they are biocompatible, inexpensive, and environmentally benign, bionanomaterials have also garnered a lot of interest. Because of their diminutive size, bionanomaterials possess remarkable characteristics that enable them to

**Table 1. Revolutionizing fish biotechnology and future prospects**

| Breakthrough | Description | Impact | References |
|---|---|---|---|
| CRISPR-Cas9 | Genome editing tool enabling precise modifications in fish DNA. | Enhanced disease resistance, improved growth rates, and selective breeding. | Bai et al. [29] |
| Aquaponics | Integration of aquaculture and hydroponics, creating a sustainable system where fish waste fertilizes plants, and plants clean the water for fish. | Increased efficiency in resource usage, minimized environmental impact. | Kloas et al. [30] |
| Bioluminescence | Incorporation of bioluminescent genes from other organisms into fish for various applications, including tracking and pollution detection. | Enhanced monitoring capabilities, novel research opportunities. | Syed and Anderson, [31] |
| Nanotechnology | Development of nanoscale devices for drug delivery, disease detection, and environmental monitoring within fish populations. | Precise targeting of treatments, early disease detection, improved environmental surveillance. | Rather et al. [32] |
| Data Analytics | Utilization of big data and machine learning algorithms for analyzing fish behavior, population dynamics, and ecosystem interactions. | Enhanced understanding of fish ecology, optimized management strategies. | Gladju et al. [33] |
| Synthetic Biology | Engineering of synthetic biological circuits to control gene expression, metabolic pathways, and physiological processes in fish. | Customized traits for specific aquaculture needs, potential for creating novel functionalities | Leggieri et al. [34] |
| Blockchain | Implementation of blockchain technology for traceability and transparency in the fish supply chain, ensuring food safety and combating illegal fishing practices. | Improved consumer confidence, strengthened regulatory compliance. | Tsolakis et al. [35] |

thrive in a wide range of industries, including agriculture, environmental protection, biomedicine, and material science. Investigations on the superior properties of biologically produced nanomaterials and nanocomposites in water purification, pesticide detection, and heavy metal and inorganic dye removal have recently come to light. Because of their useful characteristics, nanobiotechnological methods outperform conventional ones in every field [23].

**Nanoparticles as Probes:** In living organisms, nanoparticles operate as sensors, probes, or delivery mechanisms for biomolecules. Conversely, nanoparticles can alter the physical properties of fish food in addition to increasing the bioavailability and stability of nutrition components. Nanomaterials, even when added in minute amounts, can significantly improve the physical characteristics of food pellets [24].

**Bioremediation:** Bioremediation is a technique that employs biological agents to break down and eliminate pollutants such heavy metals, hydrocarbons, azo dye, and pesticides, transforming them into less dangerous substances [25]. Bioremediation is a commonly employed technique for converting organic pollutants into molecules that are less harmful [26]. Microorganisms are employed in bioremediation due to their capacity to transform toxic pollutants into carbon dioxide [$CO_2$], water [$H_2O$], microbial biomass, and less damaging byproducts compared to the original chemical. Various types of microorganisms can be employed for the purpose of bioremediation. One example is aerobic microorganisms like Mycobacterium, which are beneficial in breaking down pesticides and hydrocarbons [27]. These microorganisms are utilizing the contaminants as a source of carbon and energy. Phanaerochaete

**Table 2. Fish biotechnology: Advancing the aquatic frontier**

| Area | Description | References |
|---|---|---|
| Genetic Engineering | Utilizing CRISPR-Cas9 and other techniques for precise genetic modifications in fish | Jia *et al*. [36] |
| Aquaculture Systems | Implementing advanced aquaponics and recirculating aquaculture systems for sustainability | Love *et al*. [37] |
| Disease Management | Developing vaccines and novel treatments to combat diseases in farmed fish populations | Wang, [38] |
| Environmental Monitoring | Employing biotechnology for real-time monitoring of water quality and ecosystem health | Boyd, [39] |
| Nutritional Enhancement | Engineering fish feeds for optimized nutrition and enhanced growth rates | Gatlin *et al*. [40] |

chrysosporium, a type of fungi that can break down lignin, has been employed in the process of bioremediation to eliminate organic pollutants such polycyclic aromatic hydrocarbons (PAHs), chlorobenzene, and synthetic colors. The white rot fungi produce extracellular oxidative enzymes that degrade lignin found in hazardous compounds [28].

## 8. FUTURE DIRECTIONS AND CHALLENGES

In recent years, biotechnology has made tremendous strides, opening the door to game-changing innovations in many other sectors. But as we go out on this path of innovation, it is critical to think forward and solve the problems that may arise. In this review, we explore the new developments, possible directions, and challenges in the rapidly evolving biotech industry.

### 8.1 Future Directions

**1. Personalized Medicine:** Tailoring treatments to individual genetic profiles holds immense promise for enhancing efficacy and minimizing side effects. The integration of genomics, proteomics, and machine learning algorithms is poised to drive personalized medicine to new heights.

**2. Synthetic Biology:** Harnessing the power of engineered biological systems enables the production of novel biomaterials, biofuels, and pharmaceuticals. Advancements in gene editing technologies like CRISPR-Cas9 are expanding the toolkit for designing custom organisms with precise functionalities.

**3. Biomanufacturing:** Innovations in bioprocessing and fermentation techniques are revolutionizing the production of biopharmaceuticals, enzymes, and sustainable chemicals. Scalable manufacturing platforms and automation solutions are streamlining production workflows and reducing costs [41-42].

### 8.2 Challenges

**1. Ethical Considerations:** As biotechnology blurs the lines between what is natural and artificial, ethical dilemmas surrounding genetic engineering, gene editing, and cloning become increasingly complex. Striking a balance between innovation and ethical responsibility is paramount.

**2. Regulatory Hurdles:** The evolving nature of biotechnological innovations poses challenges for regulatory frameworks to keep pace. Ensuring the safety, efficacy, and ethical use of emerging biotechnologies requires agile regulatory approaches that foster innovation while safeguarding public health and the environment.

**3. Data Security and Privacy:** With the proliferation of genomic data and personalized health information, protecting sensitive data from cyber threats and unauthorized access is a pressing concern. Robust data encryption, access controls, and regulatory safeguards are essential to uphold patient privacy and confidentiality.

## 9. CONCLUSIONS

In conclusion, the domain of fish biotechnology is poised for a paradigm shift, driven by a confluence of significant developments and auspicious future potential. By employing novel genetic engineering methodologies, including CRISPR-Cas9, researchers have gained entry to unparalleled prospects for augmenting vital aquaculture attributes, including growth rates, resistance to diseases, and nutritional composition. Furthermore, progress in omics technologies has yielded more profound understandings of the molecular processes that govern fish biology, thereby facilitating the development of targeted nutrition regimens and precision breeding techniques. Fish biotechnology exhibits tremendous potential in addressing the escalating worldwide seafood requirement while simultaneously alleviating the strains on untamed fish populations and ecosystems. By cultivating interdisciplinary cooperation, encouraging novel ideas, and maintaining ethical principles in our approach, we can effectively harness the complete capabilities of fish biotechnology to fundamentally transform aquaculture and secure a sustainable trajectory for future generations.

## FUTURE PROSPECTS

Responsible innovation, cross-sector cooperation, and interdisciplinary study are essential for biotechnology's future success. Unlocking the full potential of biotechnology to address global concerns and improve human health and well-being requires resolving key challenges, embracing emerging technologies, and building an ecosystem of collaboration and transparency.

## COMPETING INTERESTS

Authors have declared that no competing interests exist.

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