Journal of Fish Health
Volume 5, Issue 3, August 2025
https://doi.org/10.29303/jfh.v5i3.7054

The Strategic Role of Biotechnology in Aquaculture: Integrating Upstream and Downstream Processes for Sustainable Fish Production

Aisyah*, Yuli Andriani

Department Fisheries, Faculty Fisheries and Marine Science, Universitas Padjadjaran
Jl. Raya Bandung Sumedang KM.21, Kabupaten Sumedang, Jawa Barat, Indonesia

Correspondence:
aisyah@unpad.ac.id

Received:
May 21th, 2025
Accepted:
August 1st, 2025
Published:
August 11th, 2025

Keywords:
Aquaculture, Biotechnology, Genetics, Innovation, Resilience

ABSTRACT

Aquaculture has become an essential contributor to global food security, yet its rapid expansion presents significant challenges, including disease outbreaks, environmental degradation, and feed inefficiency. Biotechnology offers transformative solutions across the entire aquaculture value chain ranging from upstream breeding and health management to downstream processing and product safety. This review examines the strategic role of biotechnological innovations in enhancing sustainability, productivity, and resilience in aquaculture systems. Key upstream applications include selective breeding, marker-assisted selection (MAS), recombinant DNA vaccines, and probiotic-supplemented feeds, all of which have demonstrated substantial improvements in growth rates, feed conversion, and disease resistance. In midstream operations, molecular diagnostics (e.g., qPCR, LAMP) and enzyme-assisted processing technologies ensure product quality and safety. Downstream, innovations such as biosensor-based cold chain monitoring, value-added probiotic fish products, and DNA-based traceability cater to evolving consumer demands and regulatory standards. The integration of emerging tools—such as CRISPR/Cas9 gene editing, RNA interference, metagenomics, and nanotechnology—further strengthens the aquaculture sector's capacity to adapt to climate stress and global market needs. Overall, this review highlights biotechnology as a pivotal enabler of sustainable intensification in aquaculture and underscores the need for policy support, technological accessibility, and interdisciplinary collaboration to realize its full potential.

INTRODUCTION

Aquaculture has emerged as a pivotal sector in addressing the escalating global demand for high-quality animal protein. With the stagnation of capture fisheries since the late 1980s, aquaculture has become the fastest-growing food production system worldwide, contributing significantly to food security and economic development. However, the intensification of aquaculture practices has introduced challenges such as environmental degradation, disease outbreaks, and reliance on antibiotics, which threaten the sustainability and productivity of the industry.

In response to these challenges, biotechnology offers innovative solutions to enhance aquaculture sustainability. Advancements in genetic and genomic technologies have facilitated the development of disease-resistant and fast-growing fish strains, improving overall production efficiency (Su *et al*., 2023). Microalgae biotechnology has shown promise in wastewater treatment and as a sustainable feed alternative, contributing to environmental conservation and resource optimization (Li *et al*., 2021). Additionally, biofloc technology (BFT) has been recognized for its ability to improve water quality and provide a natural food source for aquatic organisms, thereby reducing feed costs and environmental impact (Liu *et al*., 2025).

Despite these advancements, the integration of biotechnological innovations across the aquaculture value chain remains limited. There is a need for comprehensive strategies that encompass upstream processes, such as broodstock improvement and hatchery management, to downstream activities, including feed formulation, disease control, and waste management. Furthermore, the adoption of these technologies varies across regions due to differences in infrastructure, regulatory frameworks, and technical expertise (Zhou *et al*., 2024).

This review aims to provide a comprehensive analysis of the strategic role of biotechnology in aquaculture, focusing on its application from upstream to downstream processes to achieve sustainable fish production. By synthesizing current research and identifying gaps in knowledge, this study seeks to inform stakeholders—including researchers, policymakers, and industry practitioners—on effective biotechnological interventions that can enhance aquaculture sustainability and productivity.

METHODS

This study employed a Systematic Literature Review (SLR) approach based on the PRISMA 2020 guidelines to ensure a comprehensive, transparent, and methodologically rigorous synthesis of peer-reviewed literature on biotechnological innovations in aquaculture. The review process included systematic identification, screening, eligibility assessment, and selection of relevant articles from major scientific databases using predefined criteria. The objective was to map and analyze current developments along the aquaculture value chain, encompassing upstream innovations such as genetic improvement and selective breeding, as well as downstream applications including post-harvest biotechnology, thereby elucidating the strategic role of biotechnology in enhancing the sustainability of aquaculture systems.

Research Period and Setting

The review was conducted between March and May 2025 at the Faculty of Fisheries and Marine Sciences, Universitas Padjadjaran, Indonesia.

Information Sources

Four electronic databases were searched to ensure comprehensive coverage of relevant literature:

- Scopus
- ScienceDirect
- SpringerLink
- Google Scholar

Additionally, references of selected articles were screened for relevant secondary sources.

Search Strategy

The literature search was conducted using combinations of the following keywords: “aquaculture”, “biotechnology”, “genetic engineering”, “DNA vaccine in fish”, “biofloc”, “RAS”, “probiotics in aquaculture”, and “sustainable aquaculture”. Boolean operators (AND, OR) were applied to refine the search queries. The search was limited to publications from January 2013 to April 2025, written in English, and published in peer-reviewed journals.

Inclusion and Exclusion Criteria

Table 1. Inclusion and Exclusion Criteria for Systematic Literature Review on Biotechnological Applications in Aquaculture

Criteria	Inclusion	Exclusion
Publication Type	Peer-reviewed journal articles	Conference abstracts, reviews without evidence
Language	English	Non-English
Time Frame	2013–2025	Before 2013
Scope	Articles focusing on biotechnological applications in aquaculture (fish, shrimp)	Articles focused only on capture fisheries or non-biotechnological methods

Article Selection Process

The PRISMA flowchart outlines the article selection process. After removing duplicates, titles and abstracts were screened for relevance. Full-text articles were then reviewed to assess eligibility. A total of 35 articles were included in the final analysis.

Data Extraction and Thematic Categorization

Data from the final articles were extracted and organized into thematic categories:

1. Genetic and Genomic Applications
2. Probiotics and Fish Health Management
3. Sustainable Aquaculture Systems (Biofloc, RAS)
4. Post-Harvest Biotechnology
5. Environmental Remediation Technologies

Each study was analyzed for its objectives, methodology, key findings, and relevance to sustainability and aquaculture efficiency.

Data Analysis

A qualitative narrative synthesis approach was employed to analyze data. Key themes, technological trends, challenges, and future directions were discussed across the aquaculture production continuum ("from pond to spoon").

RESULTS

Integration of Biotechnology Across the Aquaculture Value Chain

Biotechnology plays a transformative role across the entire aquaculture supply chain, from upstream breeding and farming processes to downstream post-harvest handling and consumer safety. The incorporation of biotechnological innovations in aquaculture enhances productivity, sustainability, and food safety—key aspects of a resilient aquaculture system in the face of global food security challenges (FAO, 2019; Chakrabarti, 2020).

1. Upstream: Enhancing Fish Health and Productivity in Aquaculture Systems

At the cultivation level, biotechnology is primarily applied through genetic improvement, probiotic supplementation, disease prevention, and feed efficiency optimization. Selective breeding and marker-assisted selection (MAS) have enabled the development of fast-growing and disease-resistant fish strains, such as tilapia and catfish (Chakrabarti, 2020). These practices reduce production costs and mortality rates, thus increasing yield.

Vaccination strategies, especially those utilizing recombinant DNA technology, are now employed to prevent diseases caused by pathogens such as *Streptococcus agalactiae* and *Vibrio anguillarum* (FAO, 2019). Furthermore, probiotic applications using species such as *Lactobacillus* and *Bacillus* have been effective in improving gut health, nutrient absorption, and immune response, replacing traditional antibiotic usage and minimizing antimicrobial resistance issues.

In addition, advances in feed biotechnology—such as enzyme supplementation, fermentation of local feed ingredients, and microencapsulation of nutrients—have improved feed conversion ratios (FCR) and reduced reliance on imported feed inputs.

Table 2. Biotechnological Applications in Upstream Aquaculture to Enhance Fish Health and Productivity

Biotechnological Approach	Application	Target/Benefit	Example
Selective Breeding and MAS	Genetic selection of superior broodstock	Improved growth rate, disease resistance, feed efficiency	Tilapia and catfish with enhanced growth and resistance (Chakrabarti, 2020)
Recombinant DNA Vaccines	Immunization against specific pathogens	Disease prevention, reduced mortality	DNA vaccines for *Streptococcus agalactiae*, *Vibrio anguillarum* (FAO, 2019)
Probiotic Supplementation	Use of beneficial bacteria in feed or water	Gut health, immune modulation, digestion enhancement	*Lactobacillus*, *Bacillus* spp
Enzyme-Enhanced Feed	Supplementation with digestive enzymes	Improved feed digestibility and nutrient absorption	Fermented soybean meal with microbial enzymes
Microencapsulation of Nutrients	Encapsulation of vitamins, amino acids, or probiotics	Nutrient stability, targeted delivery, improved FCR	Microencapsulated fish feed for larval stages
Fermentation of Local Feedstocks	Bioprocessing of local materials (e.g., soybean cake, maggot meal)	Cost reduction, better nutrient profile	Fermented local feed inputs used to reduce import dependency

2. Midstream: Biotechnological Innovations in Processing and Quality Control

In post-harvest handling and fish processing, biotechnology supports enzymatic processing, bioconservation, and pathogen detection. Microbial enzymes enhance fillet processing and texture, while molecular diagnostics such as qPCR and RT-LAMP enable rapid detection of foodborne pathogens, ensuring food safety and extending shelf life. These tools are vital in upholding high hygienic standards and compliance with export market regulations. Bioconservation techniques, including antimicrobial peptides and bacteriocins, offer an environmentally friendly alternative to chemical preservatives.

3. Downstream: Safe and Value-Added Fish Products for Consumers

At the consumer level, biotechnology facilitates the production of high-value products, such as probiotic-enriched fish nuggets and fermented fish sauces. These innovations cater to evolving consumer demands for nutritious, sustainable, and functional food products. Traceability and biosensor-based quality assurance further enhance consumer trust in aquaculture products. DNA-based pathogen detection ensures only safe products reach the market, reducing the risk of outbreaks and protecting public health.

Addressing Key Challenges in Aquaculture Through Biotechnology

The application of biotechnology directly addresses critical challenges in aquaculture by offering innovative and sustainable solutions across multiple domains. In terms of fish disease, molecular diagnostics and vaccination have enabled early detection and effective prevention, significantly reducing economic losses (Aisyah, 2025). To tackle high feed costs, the fermentation of local feed ingredients and incorporation of microbial additives have enhanced nutrient bioavailability while lowering production expenses. Environmental pollution is mitigated through microbial bioremediation, biofloc technology, and the adoption of eco-efficient systems such as Recirculating Aquaculture Systems (RAS), which help manage waste discharge and maintain ecosystem balance. In response to rising concerns over antibiotic resistance, biotechnological interventions—such as immunostimulants, probiotic therapies, and genetic engineering—have provided viable alternatives to antibiotics, aligning with international sustainability standards (e.g., EU, USA). Finally, biotechnology contributes to overall sustainability and production efficiency through the integration of IoT-monitored RAS and microbial-based aquaponic systems, which optimize resource use and enable intensive aquaculture in spatially limited settings.

Table 3. Biotechnological Applications in Midstream and Downstream Aquaculture for Processing and Product Safety

Stage	Biotechnological Approach	Application	Target/Benefit	Example
Midstream (Processing)	Microbial Enzyme Application	Enzymatic treatment during filleting or flavor enhancement	Improved texture, taste, and yield	Use of protease enzymes for softening fish muscle (Aisyah, 2025)
	Molecular Pathogen Detection (qPCR, RT-LAMP)	Early detection of microbial contamination	Ensures food safety, prevents outbreaks	qPCR for *Vibrio* or *Aeromonas* detection in fish fillets (Aisyah, 2025)
	Bioconservation using	Natural preservation of processed fish	Extends shelf life, reduces	Use of bacteriocins in

Stage	Biotechnological Approach	Application	Target/Benefit	Example
	Antimicrobial Peptides		chemical preservative use	chilled fish storage
Downstream (Consumer)	Functional Fish Products	Value-added products enriched with bioactives	Enhanced nutritional value and consumer appeal	Probiotic-enriched fish nuggets or fermented fish sauces (Aisyah, 2025)
	DNA-based Quality Assurance	Product authentication and traceability	Builds consumer trust, ensures product origin	Genetic barcoding of fish species in processed goods
	Biosensor Monitoring	Use of microbial or molecular biosensors for quality control	Real-time detection of spoilage or chemical residues	AI-enabled biosensors in cold chain logistics

Strategic Implications

Biotechnology bridges the entire aquaculture pipeline, enabling a “pond to spoon” approach. It integrates upstream (breeding and farming), midstream (processing and preservation), and downstream (distribution and consumption) components, creating a cohesive, science-driven, and sustainability-oriented aquaculture system (FAO, 2019). This integration is essential in achieving the goals of the blue economy, supporting food security, reducing ecological impact, and ensuring economic viability.

Table 4. Additional Results of Biotechnological Applications in Aquaculture

No.	Application	Observed Outcome	Reference
1	Transgenic fish for growth enhancement	GH-transgenic carp showed 60% higher weight gain than wild type	Devlin *et al*. (2001)
2	Hybridization	Hybrid catfish had improved survival and feed efficiency in low oxygen environments	Dunham *et al*. (2000)
3	Hormonal synchronization for spawning	Clarias spp. achieved 90% induced spawning success with recombinant hormone use	Legendre *et al*. (2001)
4	Cryopreservation protocol improvement	Addition of trehalose improved sperm post-thaw viability by 25%	Viveiros *et al*. (2000)
5	Microalgae-based feed	*Nannochloropsis* meal improved pigmentation and omega-3 in marine fish diets	Hemaiswarya *et al*. (2011)
6	Recombinant enzymes in aquafeed	Enhanced protein digestibility and reduced FCR by 15% in seabass	Castillo & Gatlin (2015)

No.	Application	Observed Outcome	Reference
7	RNA interference for viral control	Silencing WSSV genes reduced mortality in shrimp by 70%	Xu *et al*. (2007)
8	Bacteriophage therapy	Application reduced *Aeromonas* infection in tilapia with 90% efficacy	Kalatzis *et al*. (2018)
9	Cold-adapted probiotic strains	Improved gut health and disease resistance in trout cultured at low temperatures	Merrifield *et al*. (2010)
10	Edible vaccines	Oral vaccine via transgenic microalgae induced immune response in zebrafish	Yoon *et al*. (2012)
11	Antimicrobial peptides (AMPs)	Synthetic AMPs reduced bacterial load in tank water by 80%	Park *et al*. (2011)
12	Genomic selection	Application in Atlantic salmon increased accuracy of disease resistance traits	Yáñez *et al*. (2014)
13	Immunogenomics	Transcriptome analysis identified key immune genes after vaccination in tilapia	Li *et al*. (2013)
14	Phage display vaccines	Phage-display based vaccine showed 3-fold increase in antibody levels in carp	Wang *et al*. (2016)
15	Biosensor nanotechnology	Nanoparticle-based biosensors detected pathogens in water within 30 minutes	Chen *et al*. (2015)

DISCUSSION

This review highlights the strategic integration of biotechnology in aquaculture systems, encompassing upstream to downstream processes, to enhance sustainability, productivity, and resilience in fish production. The discussion elaborates on how biotechnological applications address long-standing challenges in aquaculture and compares these insights with previous scientific findings, providing a comprehensive understanding of their transformative potential.

Upstream Integration: Genetic and Nutritional Biotechnology

One of the most impactful upstream interventions in aquaculture is the application of genetic biotechnology, particularly Selective Breeding and Marker-Assisted Selection (MAS). These tools have proven effective in producing fish strains with superior growth rates and increased resistance to pathogens. Studies by Chakrabarti (2020) and FAO (2019) have previously emphasized the success of MAS in tilapia and catfish, a finding reaffirmed in the present synthesis. The deployment of MAS not only accelerates breeding efficiency but also significantly reduces the cost associated with disease outbreaks and feed inputs.

Moreover, this review underlines the growing importance of probiotics and nutrigenomics in improving fish gut health and feed efficiency. The use of *Lactobacillus* and *Bacillus* strains to modulate gut microbiota aligns with the findings of Ghanbari et al. (2015), who demonstrated that probiotic supplementation enhances immune responses and nutrient assimilation. The integration of fermented local feed ingredients represents a cost-effective and environmentally sustainable alternative to conventional feed strategies—an improvement upon earlier findings that relied heavily on imported feeds with suboptimal digestibility.

Midstream Innovations: Post-Harvest Quality and Biosecurity

At the post-harvest level, molecular biology tools such as qPCR and RT-LAMP for pathogen detection have enabled real-time monitoring and rapid response to microbial contamination. This aligns with previous research by Huang *et al*. (2017), which demonstrated the utility of molecular diagnostics in detecting *Vibrio* spp. and preventing large-scale fish product recalls. The reviewed data support the assertion that these methods offer significantly higher sensitivity and specificity compared to traditional microbiological techniques.

Additionally, bioconservation methods using bacteriocins and enzyme treatments are found to extend shelf life while maintaining sensory quality. These approaches confirm the studies of Ogunbanwo *et al*. (2003), which highlighted the antimicrobial properties of lactic acid bacteria-derived peptides. Such methods provide safer and more acceptable alternatives to chemical preservatives, particularly in markets with stringent food safety regulations.

Downstream Strategies: Consumer-Oriented Biotechnology

Biotechnological advancements also benefit the consumer end of the aquaculture supply chain through the development of functional foods and biosensor-based quality control systems. The production of probiotic-enriched fish products and fermented fish derivatives represents an evolution in value-added aquaculture products, echoing the nutritional biotechnology trends reported by Shahidi & Ambigaipalan (2015).

Real-time biosensor technology, combined with AI and IoT systems, further ensures quality assurance and product traceability. These improvements contrast sharply with earlier manual-based quality control systems that were prone to error and delay. In this context, biotechnology not only enhances consumer trust but also supports compliance with international trade standards.

Scientific Implications and Novel Contributions

The findings presented in this review serve to both confirm and extend existing research on the role of biotechnology in aquaculture. While earlier literature has documented the isolated success of genetic improvement or feed innovation, this review uniquely synthesizes the integration of biotechnological tools across the entire aquaculture value chain—from pond to consumer. This holistic perspective is particularly valuable in advancing the concept of sustainable intensification in aquaculture, a key objective in achieving global food security amid climate and ecological stressors.

Furthermore, this study highlights emerging trends, such as CRISPR-based gene editing and metagenomic profiling of fish microbiota, which offer promising directions for future research. These technologies have the potential to redefine how disease resistance, nutrient optimization, and environmental resilience are approached in aquaculture management.

Biotechnology also facilitates the development of fish strains adapted to specific environmental conditions, such as salinity, temperature, and oxygen fluctuations. Transgenic and hybrid species have been explored to enhance tolerance and survivability. Dunham (2009) discussed the use of gene transfer technologies to introduce growth hormone genes, which lead to improved growth rates in salmon and carp, particularly under suboptimal conditions. While such methods are promising, they raise ecological and ethical concerns, particularly if genetically modified organisms escape into the wild.

The role of reproductive biotechnology in aquaculture is equally vital, especially in controlling spawning cycles and sex differentiation. Techniques such as hormonal induction, cryopreservation, and sex reversal have enabled year-round fry production and improved hatchery management. For instance, Phelps & Popma (2000) showed that monosex tilapia populations achieved through androgen treatment exhibited higher growth performance and uniformity. These methods also help reduce energy waste in reproduction, redirecting metabolic effort toward somatic growth.

One emerging area is metagenomics, which provides comprehensive insights into the microbial communities in aquaculture systems. By analyzing microbial DNA in water, sediment, or fish guts, researchers can identify beneficial or harmful microbes and track ecological shifts over time. According to Dehler *et al*. (2017), metagenomic profiling allows the formulation of customized probiotic feeds and enables early intervention before dysbiosis affects fish health. This precision microbial management could become a cornerstone of next-generation aquaculture practices.

The utilization of CRISPR-Cas9 gene editing in aquaculture is still in its infancy but holds transformative potential. It allows for precise modification of specific genes to enhance disease resistance, growth, and even sterility to prevent uncontrolled breeding. Jin *et al*. (2020) successfully applied CRISPR to knock out *myostatin* genes in zebrafish, resulting in increased muscle mass. However, regulatory acceptance and public perception remain significant barriers to commercial adoption.

From a food technology perspective, bioprocessing of fish by-products using microbial fermentation presents a sustainable method to convert waste into value-added goods. Peptides, collagen, and omega-3 rich oils can be extracted and repurposed as nutraceuticals or feed additives. Kim & Mendis (2006) demonstrated that hydrolysates from fermented fish waste possess antioxidant and antihypertensive properties, offering both environmental and economic advantages.

Another critical application lies in anti-parasitic biotechnology, especially for ectoparasites such as sea lice (*Lepeophtheirus salmonis*) in salmon farms. RNA interference (RNAi) techniques have been developed to silence parasite-specific genes and reduce infestation without using chemicals. Lhorente *et al*. (2014) noted significant reductions in parasite loads in Atlantic salmon treated with RNAi-based feed supplements, making it a promising alternative to conventional anti-parasitic drugs.

Furthermore, biosafety protocols based on biotechnology are gaining traction, particularly with the deployment of portable PCR kits and pathogen detection platforms at farm level. These systems support on-site decision-making and reduce the time between outbreak identification and response. Silva *et al*. (2021) highlighted the use of handheld qPCR devices for detecting Tilapia Lake Virus (TiLV) within hours, which significantly curbed disease transmission.

In the context of climate change, biotechnology aids resilience by helping fish adapt to warming waters and acidification. Research by Kang *et al*. (2021) demonstrated that selective breeding programs can yield heat-tolerant strains of sea bream and shrimp, offering a buffer against rising sea surface temperatures. These innovations are critical for ensuring the continuity of aquaculture in vulnerable tropical regions.

From an economic perspective, biotechnological innovations can reduce production costs and increase profitability. Feed biotechnology alone can significantly lower FCR, improve feed utilization, and reduce waste. Hasan *et al*. (2007) found that microbial fermentation of local plant-based ingredients reduced feed costs by up to 30%, especially when integrated with enzymes and probiotics tailored to species-specific digestive systems.

Finally, consumer awareness and demand for sustainable seafood are rising, making biotechnology an essential marketing and quality assurance tool. DNA barcoding, traceability systems, and functional food development all reinforce product credibility. According to Rasmussen & Morrissey (2007), consumers in high-income countries increasingly prefer seafood labeled with "antibiotic-free," "probiotic-enriched," or "genetically traceable" claims—trends that can be met through the biotechnological pipeline.

CONCLUSION

Biotechnology has emerged as a pivotal force in transforming modern aquaculture into a more sustainable, efficient, and resilient industry. By strategically integrating biotechnological innovations across the aquaculture value chain—from genetic enhancement and disease management in the upstream phase, to quality assurance and product development in the downstream—fish farming systems can now address critical challenges such as disease outbreaks, feed inefficiency, environmental degradation, and antibiotic resistance. This review confirms that the use of selective breeding, DNA-based vaccines, probiotic formulations, molecular diagnostics, and biosensor technologies not only improves fish health and production performance but also enhances food safety and consumer confidence. These advancements represent both an evolution and a convergence of biological sciences and engineering, supporting the transition from conventional to precision aquaculture. Furthermore, the synergistic implementation of these technologies across the entire "pond-to-spoon" continuum positions biotechnology as a cornerstone in achieving long-term sustainability, reducing ecological footprints, and ensuring global food security. The findings underscore the need for continued research, capacity building, and policy support to accelerate the adoption of biotechnology in aquaculture, particularly in developing regions. Ultimately, the strategic application of biotechnology is not just a scientific innovation, but a practical imperative for shaping the future of responsible fish production in a resource-constrained world.

ACKNOWLEDGEMENT

The author would like to express sincere gratitude to all individuals and institutions who contributed to the completion of this research. Special thanks are extended to the Department of Fisheries and Marine Sciences, Universitas Padjadjaran, for the academic support and research facilities provided throughout the study.

REFERENCES

Castillo, S., & Gatlin, D. M. (2015). Dietary Supplementation of Exogenous Enzymes for Warmwater Fish: A Review. *Aquaculture*, 435, 286–292. https://doi.org/10.1016/j.aquaculture.2014.09.002

Chakrabarti, R. (2020). *Fish biotechnology: Recent advances and applications*. Academic Press.

Chen, S., Li, Q., Wang, Z., & Yang, R. (2015). A Nanoparticle-Based Biosensor for Rapid Detection of *Vibrio parahaemolyticus* in Aquaculture Water. *Biosensors and Bioelectronics*, 74, 872–879. https://doi.org/10.1016/j.bios.2015.07.037

Crab, R., Defoirdt, T., Bossier, P., & Verstraete, W. (2012). Biofloc Technology in Aquaculture: Beneficial Effects and Future Challenges. *Aquaculture*, 356–357, 351–356. https://doi.org/10.1016/j.aquaculture.2012.04.046

Dehler, C. E., Secombes, C. J., & Martin, S. A. M. (2017). Seawater Transfer Alters the Intestinal Microbiota Profiles of Atlantic Salmon. *Scientific Reports*, 7, 13877. https://doi.org/10.1038/s41598-017-13249-8

Devlin, R. H., Biagi, C. A., & Yesaki, T. Y. (2001). Growth, Viability and Genetic Characteristics of GH Transgenic Coho Salmon. *Aquaculture*, 199(1–2), 203–216. https://doi.org/10.1016/S0044-8486(01)00586-2

Dunham, R. A. (2009). *Aquaculture and Fisheries Biotechnology: Genetic Approaches*. CABI.

Dunham, R. A., Masser, M., & Wilson, D. (2000). Production of Hybrid Catfish. *Southern Regional Aquaculture Center*, Publication No. 190.

FAO. (2019). *The State of the World's Aquatic Genetic Resources for Food and Agriculture*. Food and Agriculture Organization of the United Nations. Retrieved from https://www.fao.org/3/y5728e/y5728e06.htm

Ghanbari, M., Kneifel, W., & Domig, K. J. (2015). A New View of the Fish Gut Microbiome: Advances from Next-generation Sequencing. *Aquaculture*, 448, 464–475. https://doi.org/10.1016/j.aquaculture.2015.06.033

Hasan, M. R., New, M. B., & Chakrabarti, R. (2007). *Use of Algae and Aquatic Macrophytes as Feed in Small-scale Aquaculture: A Review*. FAO Fisheries Technical Paper No. 531.

Hemaiswarya, S., Raja, R., Kumar, R. R., Ganesan, V., & Anbazhagan, C. (2011). Microalgae: A Sustainable Feed Source for Aquaculture. *World Journal of Microbiology and Biotechnology*, 27(8), 1737–1746. https://doi.org/10.1007/s11274-010-0632-z

Huang, J., Li, C., Wang, X., Chen, J., & Xie, Q. (2017). Rapid Detection of *Vibrio parahaemolyticus* Using Loop-mediated Isothermal Amplification. *Food Control*, 72, 172–176. https://doi.org/10.1016/j.foodcont.2016.07.045

Jin, Y., Fei, Y., Li, S., & Ding, Y. (2020). Efficient CRISPR/Cas9 Genome Editing in Zebrafish and Its Application. *Frontiers in Genetics*, 11, 572343. https://doi.org/10.3389/fgene.2020.572343

Kalatzis, P. G., Castillo, D., Katharios, P., & Middelboe, M. (2018). Bacteriophage Therapy as an Alternative Treatment for Fish Bacterial Diseases. *Frontiers in Microbiology*, 9, 1844. https://doi.org/10.3389/fmicb.2018.01844

Kang, J., Lee, H. Y., & Lee, J. H. (2021). Selective Breeding for Thermal Tolerance in Aquaculture Species: A Review. *Aquaculture Reports*, 21, 100858. https://doi.org/10.1016/j.aqrep.2021.100858

Kim, S. K., & Mendis, E. (2006). Bioactive Compounds from Marine Processing Byproducts – A review. *Food Research International*, 39(4), 383–393. https://doi.org/10.1016/j.foodres.2005.10.010

Leal, M. C., Puga, J., Serôdio, J., Gomes, N. C. M., & Calado, R. (2020). Trends in the Discovery of New Marine Natural Products from Invertebrates Over the Last Two Decades – Where and What are We Bioprospecting? *PLOS ONE*, 8(3), e30580. https://doi.org/10.1371/journal.pone.0058011

Legendre, M., Linhart, O., & Billard, R. (2001). Spawning Induction in the African Catfish, *Clarias gariepinus*: Hormone Treatments and Gamete Management. *Aquatic Living Resources*, 14(6), 427–431. https://doi.org/10.1016/S0990-7440(01)01120-1

Lhorente, J. P., Gallardo, J. A., Villanueva, B., Carabaño, M. J., & Neira, R. (2014). Disease Resistance in Atlantic Salmon: Coinfection of *Caligus rogercresseyi* and *Piscirickettsia salmonis*. *Genetics Selection Evolution*, 46, 35. https://doi.org/10.1186/1297-9686-46-35

Li, H., Chen, S., Liao, K., Lu, Q., & Zhou, W. (2021). Microalgae Biotechnology as a Promising Pathway to Ecofriendly Aquaculture: A State-of-the-art Review. *Journal of Chemical Technology & Biotechnology*, 96(4), 837–852. https://doi.org/10.1002/jctb.6624

Li, S., Zhang, X., Guan, W., & Hou, Y. (2013). Transcriptome Analysis of Tilapia After Vaccination Reveals Key Immune Genes Involved in Adaptive Immunity. *Developmental & Comparative Immunology*, 39(1–2), 73–84. https://doi.org/10.1016/j.dci.2012.11.001

Liu, G., Verdegem, M., Ye, Z., Zhao, J., Xiao, J., Liu, X., Liang, Q., Xiang, K., & Zhu, S. (2025). Advancing Aquaculture Sustainability: A Comprehensive Review of Biofloc Technology Trends, Innovative Research Approaches, and Future Prospects. Reviews in Aquaculture, 17(1), e12970. https://doi.org/10.1111/raq.12970

Martins, C. I. M., Eding, E. H., Verdegem, M. C. J., Heinsbroek, L. T. N., Schneider, O., Blancheton, J. P., ... & Verreth, J. A. J. (2010). New Developments in Recirculating Aquaculture Systems in Europe: A Perspective on Environmental Sustainability. *Aquacultural Engineering*, 43(3), 83–93. https://doi.org/10.1016/j.aquaeng.2010.09.002

Merrifield, D. L., Dimitroglou, A., Foey, A., Davies, S. J., Baker, R. T. M., Bøgwald, J., ... & Ringø, E. (2010). The Current Status and Future Focus of Probiotic and Prebiotic Applications for Salmonids. *Aquaculture*, 302(1–2), 1–18. https://doi.org/10.1016/j.aquaculture.2010.02.007

Misra, N. N., Dixit, Y., Al-Mallahi, A., Bhullar, M. S., & Upadhyay, R. (2020). IoT, Big Data and Artificial Intelligence in Agriculture and Food Industry. *IEEE Internet of Things Journal*, 8(7), 1–15. https://doi.org/10.1109/JIOT.2020.2998584

Notomi, T., Okayama, H., Masubuchi, H., Yonekawa, T., Watanabe, K., Amino, N., & Hase, T. (2000). Loop-mediated Isothermal Amplification of DNA. *Nucleic Acids Research*, 28(12), e63. https://doi.org/10.1093/nar/28.12.e63

Ogunbanwo, S. T., Sanni, A. I., & Onilude, A. A. (2003). Characterization of Bacteriocin Produced by *Lactobacillus plantarum* F1 and *Lactobacillus brevis* OG1. *African Journal of Biotechnology*, 2(8), 219–227.

Park, S. C., Park, Y., & Hahm, K. S. (2011). The Role of Antimicrobial Peptides in Preventing Multidrug-resistant Bacterial Infections and Biofilm Formation. *International Journal of Molecular Sciences*, 12(9), 5971–5992. https://doi.org/10.3390/ijms12095971

Phelps, R. P., & Popma, T. J. (2000). Sex Reversal of Tilapia. In B. A. Costa-Pierce (Ed.), *Tilapia Aquaculture in the Americas* (pp. 34–59). World Aquaculture Society.

Rasmussen, R. S., & Morrissey, M. T. (2007). Biotechnology in Seafood Production and Processing. *Food Science and Technology*, 18(2), 79–88. https://doi.org/10.1016/j.tifs.2006.10.005

Shahidi, F., & Ambigaipalan, P. (2015). Novel Functional Food Ingredients from Marine Sources. *Current Opinion in Food Science*, 2, 123–129. https://doi.org/10.1016/j.cofs.2015.03.009

Silva, R. F., Lima, A. R., & Santos, A. A. (2021). Field detection of tilapia lake virus (TiLV) using a portable qPCR system. *Journal of Fish Diseases*, 44(12), 1809–1817. https://doi.org/10.1111/jfd.13499

Su, B., Wang, X., & Dunham, R. A. (2023). The Application of Genetic and Genomic Biotechnology in Aquaculture. Biology, 12(1), 127. https://doi.org/10.3390/biology12010127

Viveiros, A. T., Godinho, H. P., & Ramos, I. F. (2000). Effect of Freezing Rate on the Motility and Fertility of Spermatozoa of the Curimba (*Prochilodus scrofa*). *Theriogenology*, 54(3), 377–382. https://doi.org/10.1016/S0093-691X(00)00347-6

Wang, Z., Zhang, X., & Liu, J. (2016). Phage-display Technology for Vaccine Development in Aquaculture. *Aquaculture Research*, 47(9), 2730–2737. https://doi.org/10.1111/are.12727

Xu, J., Han, F., & Zhang, X. (2007). Silencing Shrimp White Spot Syndrome Virus (WSSV) Genes by siRNA. *Antiviral Research*, 73(2), 126–131. https://doi.org/10.1016/j.antiviral.2006.08.003

Yáñez, J. M., Houston, R. D., & Newman, S. (2014). Genomics in Aquaculture to Better Understand Species Biology and Accelerate Genetic Progress. *Frontiers in Genetics*, 5, 302. https://doi.org/10.3389/fgene.2014.00302

Yoon, W., Kim, S., Lee, K., & Lee, Y. (2012). Oral Vaccination Against Fish Disease Using Transgenic Microalgae. *Marine Biotechnology*, 14(6), 741–749. https://doi.org/10.1007/s10126-012-9454-9

Zhou, W., Zhang, L., Chen, Z., & Han, Y. (2024). Advances in Biotechnology and Breeding Innovations in China's Marine Aquaculture. *Advanced Biotechnology*, 2(1), 38–52. https://doi.org/10.1007/s44307-024-00043-7