

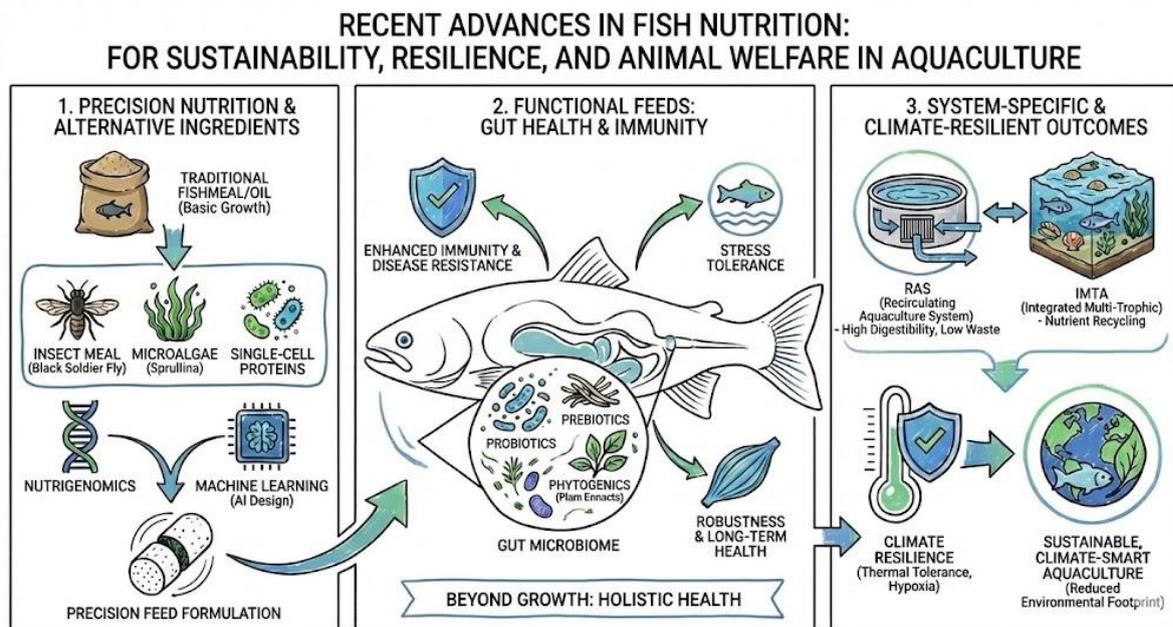
Recent advances in fish nutrition

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DOI:10.5281/FishWord.18669186



From Feed Formulation to Functional, Climate-Smart Aquaculture

Aquaculture is now the fastest-growing food production sector in the world and contributes more than half of the fish consumed globally. As the demand for fish continues to rise, the role of fish nutrition has become increasingly critical—not only for improving growth and productivity but also for ensuring fish health, environmental sustainability, and resilience to climate change. Over the past decade, fish nutrition has undergone a major transformation, moving far beyond simple feed formulation toward a more holistic and science-driven approach.

From Conventional Diets to Precision Nutrition

Traditionally, fish nutrition focused on meeting basic dietary requirements such as protein, lipid, and energy levels to support growth. While this approach was effective for improving production, it often overlooked how nutrients interact with fish physiology, immunity, and stress responses. Recent advances have shifted the focus toward **precision nutrition**, where diets are designed based on species-specific metabolism, life stage, and

environmental conditions.

Modern research has shown that not only the quantity but also the **quality and balance of nutrients** matter. For example, the ratio of essential amino acids influences muscle growth pathways, while fatty acid composition affects immune function and stress tolerance. At the same time, growing pressure on marine resources has accelerated the development of alternative feed ingredients such as insect meals, microalgae, and single-cell proteins. These ingredients reduce dependence on fishmeal and fish oil while maintaining performance and supporting sustainability.

The integration of advanced tools such as nutrigenomics and metabolomics has further deepened our understanding of how nutrients regulate gene expression and metabolic pathways. As a result, fish diets are increasingly tailored to promote not only growth but also robustness and long-term health.

Functional Feeds: Nutrition Beyond Growth

One of the most significant developments in recent years is the emergence of **functional feeds**—diets that provide health benefits beyond basic nutrition. Intensive aquaculture systems often expose fish to multiple stressors, including crowding, handling, and fluctuating water quality. These stressors weaken immunity and increase susceptibility to disease, leading to widespread use of antibiotics.

However, excessive antibiotic use has contributed to the global problem of antimicrobial resistance, raising concerns for both environmental and human health. To address this challenge, functional feeds have gained attention as a sustainable alternative. These feeds are formulated with bioactive ingredients that enhance immunity, improve stress tolerance, and reduce disease risk without relying on antibiotics.

Functional feed additives include probiotics, prebiotics, synbiotics, plant-derived compounds, algal products, antioxidants, and vitamins. Each of these components works through different mechanisms, such as strengthening gut health, enhancing immune responses, or improving nutrient absorption. By supporting the fish's natural defence systems, functional feeds play a crucial role in disease prevention and overall welfare.

Probiotics, Prebiotics and Synbiotics: Supporting Gut Health

Among functional feed additives, **probiotics** have received considerable attention. Probiotics are beneficial microorganisms administered through feed or water that improve gut health, enhance digestion, and suppress harmful pathogens. They also stimulate immune responses and help fish cope with stress. Probiotics are considered environmentally friendly and effective alternatives to antibiotics.

Closely related are **prebiotics**, which are indigestible feed components that selectively promote

the growth of beneficial gut bacteria. Common prebiotics include oligosaccharides, inulin, and yeast-derived compounds. When fermented by gut microbes, prebiotics produce metabolites that improve gut structure, nutrient absorption, and immune function.

When probiotics and prebiotics are used together, they are referred to as **synbiotics**. Synbiotics offer combined benefits by enhancing the survival and effectiveness of probiotic bacteria in the fish gut. Recent studies indicate that multi-strain probiotic formulations are often more effective than single-strain products, as different microorganisms can work synergistically to improve digestion, antioxidant capacity, and growth.

Phytogetic Feed Additives: Harnessing Plant Power

Another promising group of functional ingredients is **phytoGENICS**, which are plant-derived compounds such as herbs, spices, essential oils, and plant extracts. These compounds are naturally produced by plants as defence mechanisms and have been shown to provide similar protective effects when included in fish diets.

Phytogetic additives are valued for their antioxidant, immunostimulatory, and growth-promoting properties. They can improve digestive efficiency, enhance immune responses, and increase resistance to environmental stressors. Because they are natural and biodegradable, phytoGENICS are particularly attractive for sustainable aquaculture practices.

System-Specific Aquafeeds: One Size Does Not Fit All

Aquaculture systems vary widely, ranging from traditional ponds to advanced recirculating aquaculture systems (RAS) and integrated multi-trophic aquaculture (IMTA). Each system has unique characteristics related to water quality, waste management, and stocking density. As a result, **system-specific aquafeeds** are increasingly being developed to meet these distinct requirements.

Feeds designed for RAS, for example, prioritize high digestibility and reduced waste output to maintain water quality under high stocking densities. In IMTA systems, feeds are formulated to support nutrient recycling among different cultured species, such as fish, shellfish, and seaweeds. Tailoring feeds to specific production systems improves feed efficiency, reduces environmental impacts, and enhances farm profitability.

Climate-Resilient Aquafeeds for a Changing World

Climate change presents one of the greatest challenges to aquaculture, with rising temperatures, hypoxia, and altered ecosystem productivity affecting fish performance and survival. In response, researchers are developing **climate-resilient aquafeeds** that help fish cope with environmental stress while reducing the environmental footprint of feed production. Alternative ingredients such as microalgae and seaweeds play a key role in this strategy. These ingredients not only provide essential nutrients but also enhance stress tolerance by supporting

membrane stability and antioxidant defences. Studies have shown that algal and seaweed-based feeds can improve thermal tolerance and growth under temperature stress conditions.

Machine Learning: The Future of Aquafeed Design

As aquafeed formulation becomes more complex, traditional trial-and-error approaches are no longer sufficient. **Machine learning and decision-support tools** are emerging as powerful solutions for designing efficient and sustainable feeds. These tools can integrate nutritional, economic, and environmental data to predict fish performance and environmental emissions.

By simulating different feed formulations, machine learning models allow researchers and feed manufacturers to optimize diets before conducting costly feeding trials. This approach accelerates innovation, reduces waste, and supports the development of feeds that are both economically viable and environmentally responsible.

Looking Ahead

Recent advances in fish nutrition reflect a broader shift toward sustainability, resilience, and animal welfare in aquaculture. Functional feeds, system-specific formulations, climate-resilient ingredients, and data-driven feed design are reshaping how fish are fed and managed. As global demand for aquatic food continues to rise, adopting these innovative nutritional strategies will be essential for ensuring a secure, healthy, and sustainable future for aquaculture.

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