

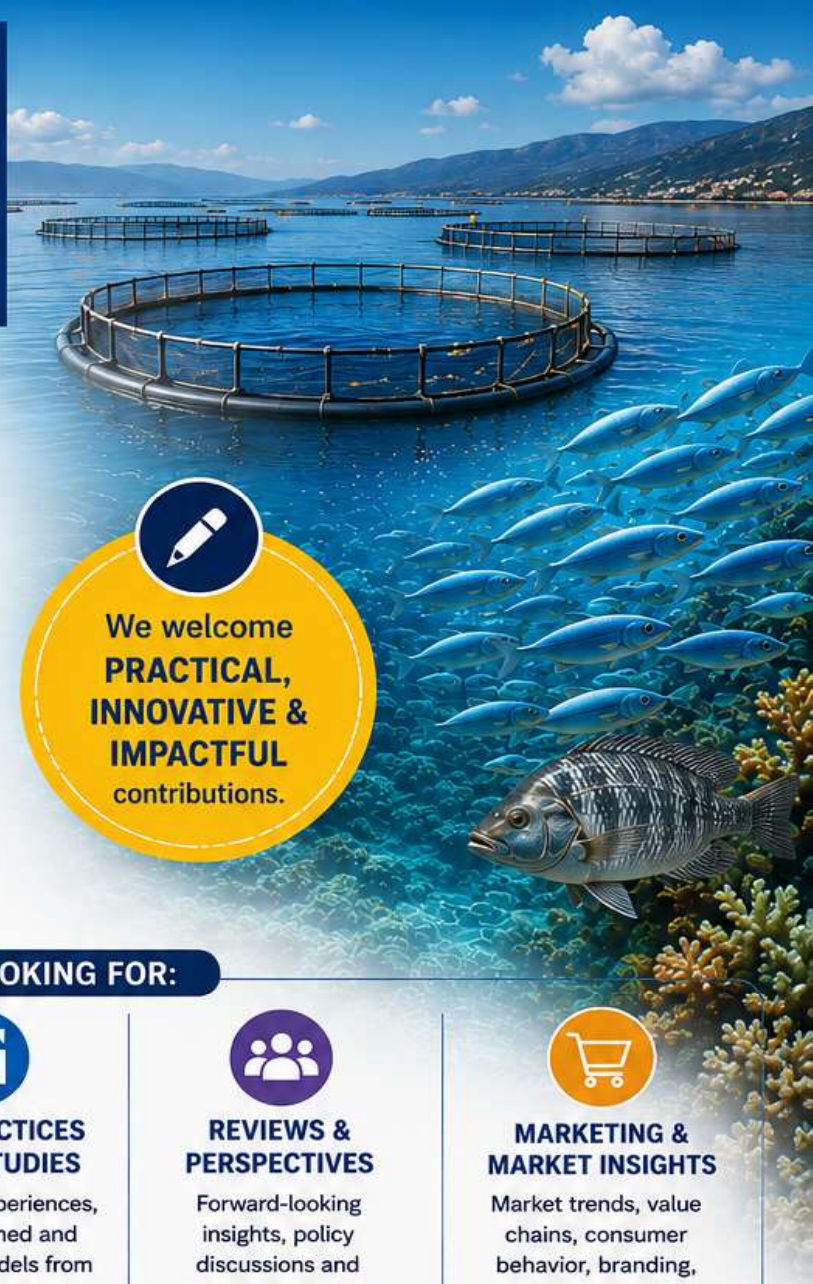
FUTURE AQUACULTURE

Volume 2, Issue 1 — November 2026

Smart Aquaculture for a Changing World

FUTURE AQUACULTURE magazine

ISSN: 3115-820X



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Innovation Is No Longer Optional

Innovation is no longer simply a competitive advantage in aquaculture—it has become a necessity. As global demand for aquatic foods continues to rise and natural resources face increasing pressure, the future of fisheries and aquaculture will depend on our ability to produce more efficiently, use fewer resources, reduce environmental impacts, and build greater resilience.

Across the sector, advances in nutrition, genetics, health management, digital technologies, artificial intelligence, and circular production systems are transforming the way we think about aquaculture. Yet innovation is not only about developing new technologies. It is also about new ways of thinking, collaborating, sharing knowledge, and addressing challenges that have remained unresolved for too long.

In this issue of Future Aquaculture, we highlight research, ideas, and perspectives that contribute to this transformation. Our aim is to connect science with industry, entrepreneurship, and practical solutions, while creating a platform for meaningful international dialogue and collaboration.

We believe the future of aquaculture will not be shaped by one technology, one institution, or one individual. It will be built collectively—through knowledge, innovation, cooperation, and action.pate in building the future of aquaculture.

Join us as we build the future of aquaculture, step by step!

Editorial Director
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Sustainable Intensification of Aquaculture: Recent Advances and Future Prospects

As global demand for aquatic foods continues to rise, aquaculture stands at a pivotal crossroads. The industry is no longer judged solely by how much fish it can produce, but by how efficiently it can convert resources into nutritious food while safeguarding ecosystems, biodiversity, and the livelihoods that depend on them. Sustainable intensification, the pursuit of greater productivity with reduced environmental impact, has therefore become the defining challenge and opportunity of modern aquaculture.

The transformation of aquaculture over the past several decades has been remarkable. Once dominated by extensive ponds and traditional farming methods, the sector is increasingly embracing sophisticated, technology-enabled systems designed to optimize water use, nutrient cycling, biosecurity, and feed efficiency. This transition reflects a broader recognition that future growth must be achieved within ecological limits rather than at their expense.

Among the most influential developments are Recirculating Aquaculture Systems (RAS), which dramatically reduce water consumption through continuous treatment and reuse. These systems offer producers unprecedented control over water quality, production conditions, and disease risks while enabling fish farming closer to consumer markets. Similarly, Biofloc Technology (BFT) has emerged as a powerful tool for nutrient recycling, converting metabolic wastes into microbial biomass that can serve as a supplementary food source, thereby improving feed utilization and reducing effluent discharge.

Integrated Multi-Trophic Aquaculture (IMTA) represents another significant milestone in sustainable intensification. By culturing fed species alongside extractive organisms such as seaweeds and shellfish, IMTA mimics natural ecosystem processes, recovering nutrients that would otherwise be lost and converting them into valuable biomass. Likewise, aquaponic systems demonstrate how fish production and plant cultivation can be integrated into highly efficient circular production systems that conserve both water and nutrients.

Perhaps the most transformative advances are occurring in the realm of precision aquaculture. Artificial intelligence, machine learning, computer vision, and Internet of Things (IoT) technologies are revolutionizing farm management by providing real-time insights into water quality, animal behaviour, feeding efficiency, and disease emergence. These tools enable producers to make data-driven decisions that reduce waste, improve animal welfare, and strengthen farm profitability.

Equally important are innovations in genetics and sustainable nutrition. Selective breeding, genomic selection, and emerging gene-editing techniques are contributing to improved growth rates, disease resistance, and feed conversion efficiency. At the same time, alternative feed ingredients including insect meals, microalgae, single-cell proteins, and agricultural by-products are reducing reliance on finite marine resources

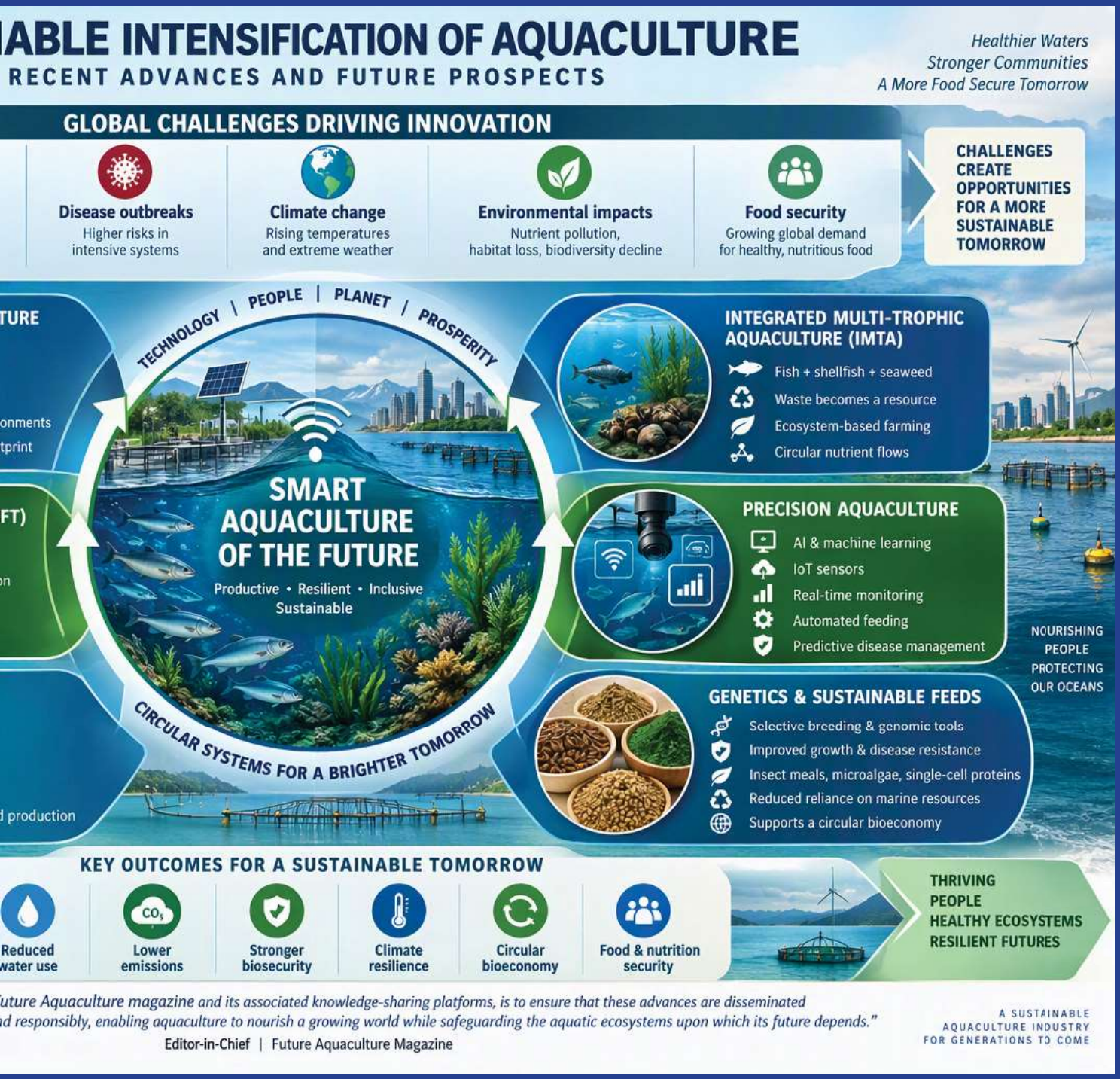


traditionally used in aquafeeds. These developments support the industry's transition toward a circular bioeconomy while enhancing long-term resilience.

Yet significant challenges remain. High capital costs, energy demands, technical expertise requirements, and regulatory complexities continue to constrain adoption of advanced technologies, particularly among small-scale farmers. Bridging this gap will require innovative financing mechanisms, farmer training, supportive public policy, and stronger collaboration between researchers, technology developers, producers, and investors.

Looking ahead, the future of aquaculture will likely be shaped by the convergence of digital technologies, renewable energy, biotechnology, and ecosystem-based production systems. Farms of the future may function as integrated, intelligent biological production units, capable of continuously optimizing performance while minimizing environmental footprints. The goal is not simply more fish, but more sustainable food production that contributes meaningfully to global food security, climate resilience, and economic development.

The message is clear: sustainable intensification is no longer an aspirational concept. It is rapidly becoming the operating model for the next generation of aquaculture. The industry now possesses the scientific knowledge, technological tools, and innovative spirit to achieve this vision. Our challenge, through Future Aquaculture magazine and its associated knowledge-sharing platforms, is to ensure that these advances are disseminated strategically and adopted inclusively and responsibly, enabling aquaculture to nourish a growing world while safeguarding the aquatic ecosystems upon which its future depends.



SEAFOOD



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The Sushi Revolution

Origins of Sushi

Sushi began more than two thousand years ago as a preservation method known as narezushi. Fish was stored with rice and salt to keep it fresh, a practice that originated in freshwater fish preservation method in the Mekong River basin (Laos, Cambodia, Thailand) and the Yangtze River valley (southern China).

When this tradition reached Japan, the recipe evolved. First, people began eating the rice along with the fish. Later, vinegar replaced fermentation, speeding up preparation and enhancing flavor. The turning point came in Tokyo in the 1820s, when Hanaya Yohei created nigiri-zushi: small hand-pressed rice topped with fresh fish, perfect for a quick bite. From there, sushi grew beyond Japan, becoming both a symbol of Japanese culture and a global culinary favorite.

Sushi in Mexico and Latin America

In 2011, I wrote an article for Entrepreneur Magazine about sushi in Mexico, highlighting its growing acceptance. At that time, Mexico had around 700 sushi restaurants. Fifteen years later, the industry has exploded, with more than **4,300 restaurants** and over **10 major chains,** representing about **2% of the national restaurant market share.**

Mexico's success with sushi is tied to its strong seafood culture. The country ranks third in Latin America for seafood consumption per capita, at **12.5 kg annually,** behind Peru (22.1 kg) and Chile (13.2 kg). Mexican sushi has also been "tropicalized," incorporating avocado, chili, and cream cheese. Today, sushi is available in all formats from food trucks to fine dining, omakase experiences where chefs prepare delicate seafood menus.

This industry generates approximately **USD 675 million annually,** making sushi one of the fastest-growing segments of Mexico's restaurant sector.

Elsewhere in Latin America, grocery stores in Brazil sell pre-packed sushi, and the country has about 9,000 sushi restaurants nationwide. Chile shows potential for more than 1,800 sushi restaurants, reflecting the region's

expanding appetite for Japanese cuisine.



Sushi in the United States

The sushi revolution has gone global. In the U.S., the National Fisheries Institute (NFI)—the largest seafood trade association—through its Sushi Council, created the U.S. Sushi Report to track its importance. According to this report, sushi has grown 9% in retail, and the U.S. sushi market is now **1.7 times larger than Japan's.**

Valued at **USD 22 billion**, the American sushi industry is driven by restaurants, retail and grocery kiosks represent the fastest growing segment.

Sushi's acceptance in the U.S. can be divided into three phases:

Early Stage Growth – Sushi as exotic, high-end cuisine in status-symbol restaurants.

Mid Stage Adoption – Expansion into affordable restaurants, reaching a wider population.

Everyday Sushi – Now available in groceries, gas stations, and convenience stores, consumed by all socioeconomic groups, especially younger generations.

Sushi in Europe

Western Europe has seen rapid growth in sushi demand, particularly in France, Germany, the UK, Spain, and Italy. Market insights firm **Spheric Research** reports there are **8,000 sushi kiosks** across Europe.

The boom has led to major consolidation: Europe's two largest retail sushi operators are merging with **Hana Group,** a global leader in retail sushi and Asian cuisine. Hana operates nearly **2,000 kiosks in 13 countries**, including Europe and the U.S., under brands like Sushi Gourmet, Genji, Mai Sushi, and Sushi Market. The combined operation aims to run **5,800 kiosks**, with a deal reportedly worth **€1.5 billion**, cementing Europe's position as a powerhouse in retail sushi.

Sushi in China

China's sushi industry is vast and growing. According to the **China Economic Research Institute**, there are **23,000 sushi restaurants.** Growth is driven more by restaurants and delivery apps than by retail kiosks, which still represent only **10–15% of outlets**.





The **Norwegian Seafood Council (NSC)** recently studied salmon consumption in tier-one cities (Shanghai, Beijing, Guangzhou, Shenzhen). They made a qualitative study where the monitored 24 people in these tier one cities for seven days, discovering that **65% of consumers eat sashimi or sushi 1–3 times per month**.

China's middle class has exploded—from **300,000 in 2000 to 184 million in 2025**. As incomes rise, lower-value species are being replaced by premium seafood. Rabobank analyst Novel Sharma notes: "Consumers are moving to more premium types of seafood."

Conclusion

Sushi, despite using relatively small amounts of seafood, has become a powerful vehicle for introducing consumers to new fish species. The cycle begins with a first taste in a restaurant, continues with kiosks in grocery stores, and eventually ends with sushi packs in home refrigerators.

One of the biggest challenges for sushi sold through convenience stores and delivery platforms is maintaining cold chain integrity. Seafood requires strict temperature control to comply with industry standards and ensure food safety.

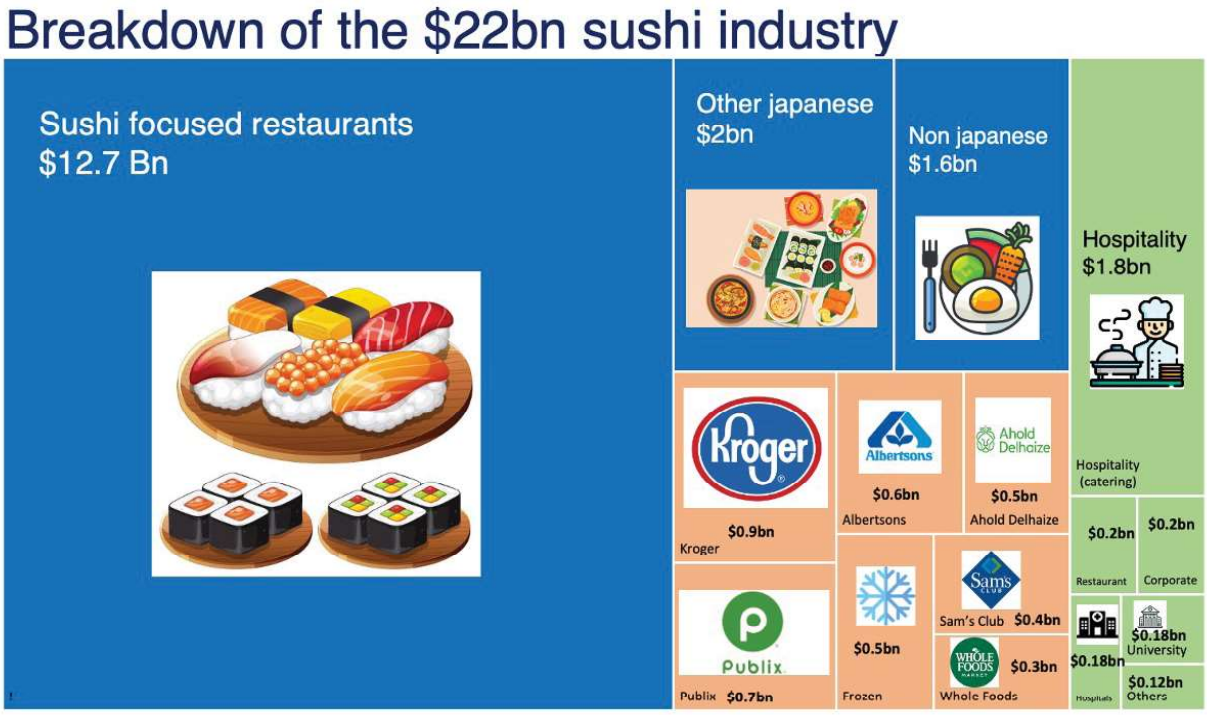
Proper handling is not only about safety—it also ensures that the fish or seafood species labeled is truly what the consumer receives. Modern solutions like blockchain and QR code tracking allow suppliers to document every step of the supply chain, from catch to counter.

Transparency in labeling and handling builds confidence, especially as sushi becomes part of everyday retail and delivery consumption.

This "sushi revolution" demonstrates how Japanese cuisine has transformed global seafood consumption, creating opportunities for producers, retailers, and chefs worldwide.

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SEAFOOD FRAUD
A GLOBAL THREAT
TO CONSUMERS. TO THE INDUSTRY. TO OUR FUTURE.

Seafood fraud is a serious global problem that undermines trust, threatens health, harms honest businesses and puts food security and the future of our oceans at risk.



"If we do not arrest the rise of seafood fraud, we are putting the whole seafood industry at risk – and with that, the health, wellbeing and food security of many nations.

THE SCALE OF THE PROBLEM

SEAFOOD IS ONE OF THE MOST TRADED FOOD COMMODITIES IN THE WORLD

Over **3 BILLION PEOPLE** rely on seafood as an important source of protein and nutrition.

UP TO **47%** OF SEAFOOD SAMPLES WORLDWIDE WERE MISLABELED

(Oceana Global Studies)



THE 11 SINS OF SEAFOOD FRAUD (Lawrence, 2022)

1. Species Substitution
2. Mislabeling
3. Unapproved Species
4. Counterfeiting
5. Concealed Damage
6. Added Substances
7. Dilution
8. Overt Enhancement
9. Misleading Information
10. Illegal Harvest
11. Document Fraud

Complex supply chains, high value and low detectability seafood a prime target for fraud.

WHY IT MATTERS

PUBLIC HEALTH RISK
Undeclared allergens, toxins, antibiotics and harmful substances can cause serious illness or even death.

CONSUMER DECEPTION
People have the right to know what they are buying. Mislabelling robs consumers of choice and trust.

ECONOMIC DAMAGE
Seafood fraud costs the global economy billions each year and undermines honest businesses.

ENVIRONMENTAL IMPACT
Illegal fishing and species substitution threaten sustainable fisheries and marine ecosystems.

FOOD SECURITY THREAT
Fraud weakens the reliability of our food systems and puts vulnerable communities at greater risk.



BUILDING THE SOLUTION

FOOD FRAUD PREVENTION REQUIRES A WHOLE-OF-SYSTEM APPROACH (Manning, 2024)

- Risk Assessment & Vulnerability Mapping
- Strong Verification & Testing
- Traceability & Transparency
- Education & Training Across the Supply Chain
- Collaboration & Information Sharing Globally
- Clear Definitions & Common Language (Spink, 2019)

SCA'S COMMITMENT: EDUCATING – EMPOWERING – PROTECTING

SCA SEAFOOD CONSUMERS ASSOCIATION

SCA is taking action through education, awareness and collaboration to tackle seafood fraud and build a trusted future.

Our initiative, I-CADMUS, focuses on the 7 key integrity risks:

- I – ILLEGAL
- C – COUNTERFEIT
- A – ADULTERATION/ ADDITION
- D – DILUTION
- M – MISLABELING
- U – UNDISCLOSED SUBSTITUTION
- S – SUBSTITUTION

A CALL TO ACTION

Governments, industry, scientists, retailers and consumers must work together.

Protecting seafood integrity protects our health, our oceans and our future.

TRUST IS THE FOUNDATION OF SEAFOOD'S FUTURE.

KNOW WHAT YOU BUY | SUPPORT TRANSPARENCY | DEMAND INTEGRITY | SECURE A HEALTHY, SUSTAINABLE FUTURE

SAFE. AUTHENTIC. SUSTAINABLE. FOR EVERYONE. EVERYWHERE.



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Producing Seafood While Restoring Oceans and Empowering Communities:

Why Mollusc Aquaculture May Be the Future of the Regenerative Blue Economy

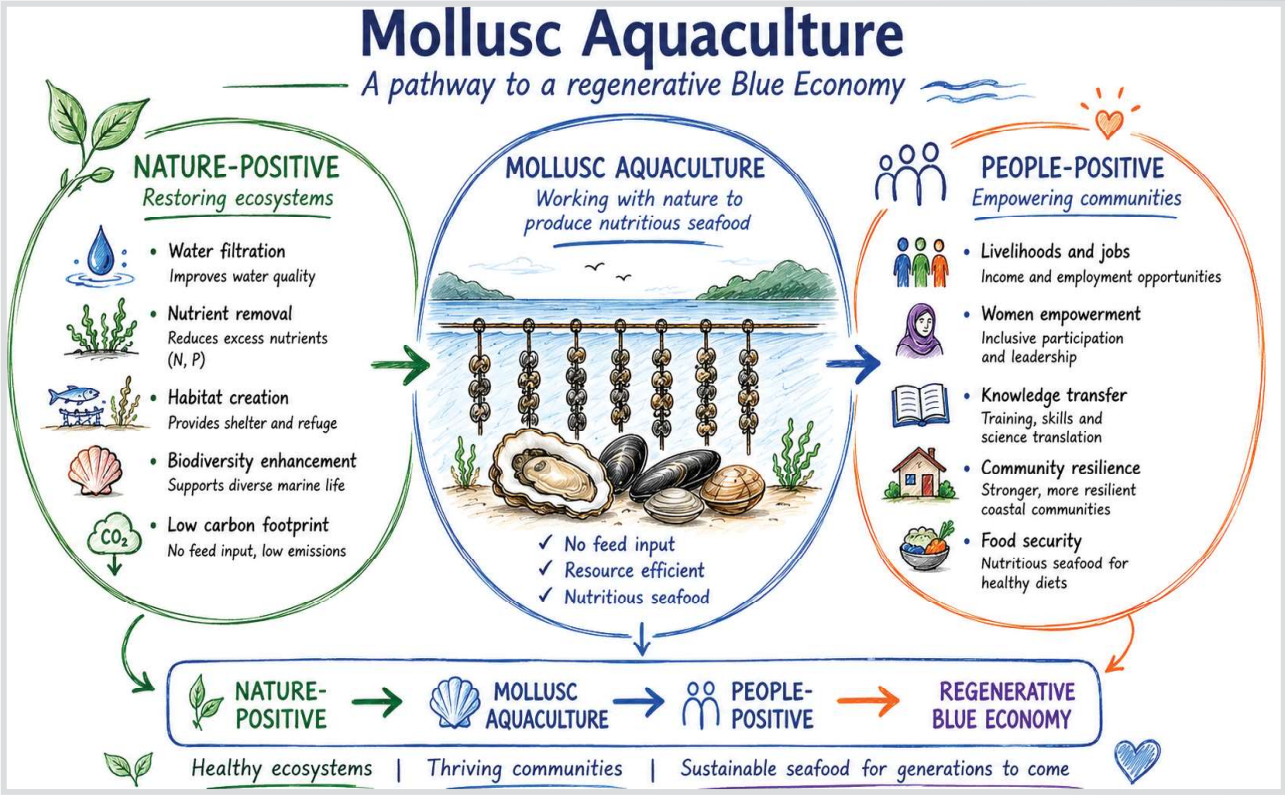
Rethinking Aquaculture in a Changing World

Humanity faces an unprecedented challenge. By 2050, the global population is expected to approach 10 billion, placing immense pressure on food production systems to provide sufficient nutrition while simultaneously addressing climate change, biodiversity loss, environmental degradation, and growing social inequalities (World Resources Institute, 2018)

The ocean is increasingly recognised as part of the solution. Aquaculture already supplies more than half of the seafood consumed globally and is expected to play an even greater role in meeting future food demands (FAO, 2024). Not all aquaculture systems are created equal. As the sector grows, there is increasing recognition that future aquaculture must do more than simply produce seafood. It must also contribute positively to ecosystem health, community well-being, and climate resilience. In this context, mollusc aquaculture stands apart.

Oysters, mussels, clams, cockles, and scallops represent one of the few forms of animal food production capable of delivering environmental, social, and economic benefits simultaneously (Gentry et al., 2017). Unlike many conventional farming systems that depend heavily on external inputs, mollusc aquaculture harnesses natural ecological processes to produce nutritious seafood while generating valuable ecosystem services (Theuerkauf et al., 2022).

As nations around the world embrace the principles of Blue



Economy, mollusc aquaculture offers a compelling vision of how food production can become both nature-positive and people-positive. More importantly, it demonstrates how aquaculture can evolve from being merely sustainable to becoming truly regenerative.

Beyond Sustainability: The Rise of Regenerative Aquaculture

For decades, sustainability has been the dominant paradigm guiding aquaculture development. The objective has largely been to minimise environmental impacts while maintaining economic viability. While this remains important, emerging global discourse is shifting towards a more ambitious goal: regeneration. Sustainability seeks to reduce harm. Regeneration seeks to create a positive impact.

A regenerative aquaculture system does not merely avoid degrading ecosystems; it actively contributes to ecosystem recovery, biodiversity enhancement, and community resilience (Theuerkauf et al., 2022). Few aquaculture sectors are better positioned to achieve these outcomes than mollusc farming.

Unlike fed aquaculture species, molluscs obtain their nutrition directly from naturally occurring phytoplankton and organic particles suspended in the water column (FAO, 2024). They require no external feed inputs during grow-out, no agricultural land for feed production, and minimal freshwater resources (Hilborn et al., 2018). As a result, their environmental footprint is among the lowest of all animal protein production systems. Yet the true value of mollusc aquaculture extends far beyond low-impact food production.

Nature-Positive Aquaculture: Working with Nature

One of the defining characteristics of mollusc aquaculture is its ability to harness ecosystem functions rather than replace them. As filter feeders, molluscs continuously process large volumes of water. A single oyster can filter tens to hundreds of litres of seawater each day, removing suspended particles, phytoplankton, and organic matter. Collectively, shellfish farms can contribute significantly to improving water clarity and maintaining ecological balance in coastal waters (van der Schatte Olivier et al., 2020).

In many coastal environments affected by nutrient enrichment, mollusc farming can help mitigate eutrophication by removing excess nutrients and enhancing water quality. These ecosystem services are increasingly recognised as valuable contributions to coastal management and environmental restoration.

Mollusc farms can also support biodiversity. Farm structures create habitat complexity that attracts fish, crustaceans, algae, and numerous other marine organisms (Callier et al., 2018). In many cases, shellfish farms function as de facto marine refuges, supporting greater biological diversity than surrounding areas.

Shellfish farming complements ecosystem restoration efforts. Around the world, oyster reef restoration projects are demonstrating how molluscs can simultaneously support seafood production, improve water quality, stabilise sediments, enhance fisheries productivity, and increase coastal resilience. A well-managed shellfish farm is therefore far more than just a seafood production unit. It is a living ecosystem that provides multiple environmental services while generating economic value.

Climate-Smart Seafood for a Low-Carbon Future

Climate change is reshaping global food systems and forcing societies to reconsider how food is produced. Compared with terrestrial livestock production, mollusc aquaculture generates exceptionally low greenhouse gas emissions (Willer & Aldridge, 2020). The absence of feed requirements eliminates a major source of carbon emissions associated with feed manufacturing, transportation, and resource extraction.

Furthermore, shellfish cultivation can contribute indirectly to

climate adaptation through its role in ecosystem restoration and coastal protection (Morris et al., 2018). Oyster reefs, for example, can function as natural breakwaters that reduce wave energy, minimise shoreline erosion, and protect vulnerable coastal habitats.

As governments and industries increasingly seek climate-smart food production systems, mollusc aquaculture offers a practical and scalable solution that aligns food security objectives with environmental stewardship.

People-Positive Aquaculture: Strengthening Coastal Livelihoods

Sustainability is ultimately about people as much as it is about ecosystems. Across many parts of the world, coastal communities are facing increasing challenges. Declining fisheries resources, habitat degradation, climate-related impacts, and economic uncertainty are placing considerable pressure on traditional livelihoods. Mollusc aquaculture presents an important opportunity for livelihood diversification and community empowerment (FAO, 2024).

Compared with many intensive aquaculture systems, shellfish farming typically requires relatively modest capital investment and operating costs. Culture systems such as longlines, racks, floating cages, and bottom culture can often be implemented by small-scale producers, making the sector particularly accessible to coastal communities.

Importantly, mollusc aquaculture creates opportunities across the value chain (Brugère et al 2019). Beyond farming itself, employment can be generated through hatchery operations, seed production, processing, packaging, marketing, tourism, and ecosystem restoration activities.

Women play especially important roles in many shellfish-producing communities (Harper et al., 2020). From seed collection and nursery management to processing and marketing, mollusc aquaculture offers meaningful opportunities for female participation and economic empowerment. Such inclusivity strengthens household resilience while promoting more equitable development. For many coastal families, shellfish farming is more than a source of income. It represents an opportunity to build resilience in an increasingly uncertain future.

Southeast Asia: An Untapped Blue Economy Opportunity

Few regions are better positioned to benefit from mollusc aquaculture than Southeast Asia. The region possesses extensive coastlines, productive estuaries, rich biodiversity, favourable climatic conditions, and generations of traditional ecological knowledge related to shellfish harvesting and culture (FAO, 2024). Yet despite these advantages, the sector remains significantly underdeveloped relative to its potential (Gentry et al., 2017).

Malaysia provides a particularly compelling example. Cockles, oysters, clams, and green mussels have long contributed to national seafood production and food security (FAO, 2024). However, much of the industry's potential remains untapped due to challenges including inconsistent seed supply, water quality degradation, disease outbreaks, limited spatial planning, and insufficient investment in innovation and value addition.

Addressing these challenges will require stronger integration between science, policy, industry, and local communities. Investments in hatchery technology, selective breeding, environmental monitoring, ecosystem restoration, and community-based mariculture programmes can help unlock the full potential





of the sector. At the same time, growing consumer demand for sustainable seafood creates opportunities for premium markets that reward environmentally responsible production practices.

The Future: Integrating Food Production, Restoration, and Community Development

The future of mollusc aquaculture lies not simply in producing more shellfish but in maximising the broader benefits that shellfish farming can deliver. Emerging approaches such as Integrated Multi-Trophic Aquaculture (IMTA) illustrate this potential. By combining fed species with extractive organisms such as shellfish and seaweeds, IMTA systems can improve nutrient recycling, reduce environmental impacts, and increase overall productivity (Uddin et al., 2025).

Similarly, ecosystem restoration initiatives are increasingly incorporating shellfish cultivation as a nature-based solution for coastal management (Theuerkauf et al., 2022). Restored oyster reefs, living shorelines, and habitat enhancement programmes are demonstrating how food production and environmental restoration can work together rather than compete for space and resources (Morris et al., 2018).

Looking ahead, new opportunities may emerge through ecosystem service valuation, blue carbon initiatives, biodiversity credits, and other innovative financing mechanisms that recognise and reward the environmental benefits generated by shellfish farming (Theuerkauf et al., 2022).

These developments signal a fundamental transformation in how aquaculture is perceived. The sector is evolving from a food production industry into a broader platform for sustainable ocean stewardship.

Conclusion: A Blueprint for the Regenerative Blue Economy

The future of aquaculture should not be measured solely by production volumes or economic returns. It should also be evaluated by its capacity to restore ecosystems, strengthen communities, and contribute to planetary health. Mollusc aquaculture demonstrates that these objectives are not mutually exclusive.

By harnessing natural ecological processes, improving water quality, supporting biodiversity, creating livelihoods, empowering coastal communities, and producing nutritious seafood with minimal environmental footprint, mollusc aquaculture embodies the very essence of a regenerative Blue Economy.

In an era defined by climate uncertainty, biodiversity decline, and growing food security challenges, the world needs solutions that work with nature rather than against it. Mollusc aquaculture offers precisely such a solution.

The most successful aquaculture systems of the future will not simply produce more seafood. They will help restore healthier oceans, create more resilient communities, and generate shared prosperity for generations to come. Mollusc aquaculture is uniquely positioned to lead this transformation.



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Interview with
Paul Robert van der Heijden



Biography:

Paul Robert van der Heijden is a distinguished Dutch expert in global aquaculture, marine biosecurity, and marine environmental conservation. With over 40 years of professional experience, he has contributed to multiple projects focused on sustainable food production through aquaculture and the protection of endangered marine environments and species. He serves on the Global Advisory Council of Future Aquaculture as Focus Area Lead – Education & Future Leaders Development, where he contributes to the development of educational initiatives, capacity building, and opportunities for the next generation of aquaculture professionals and leaders.

He currently serves as the Director of the Tope Shark Nursery Grounds Monitoring and Conservation Project development at the Wadden Sea in the Netherlands. The Wadden Sea is a protected UNESCO World Heritage Site recognized for its globally unique geological and ecological values. It is the largest continuous system of intertidal sand and mudflats in the world, where natural processes largely remain undisturbed. The site stretches along the coasts of Denmark, Germany, and the Netherlands, covering extensive tidal flats, salt marshes, dunes, and diverse habitats essential for numerous species, including migratory birds, sharks, and marine mammals.

He collaborates closely with marine aquariums and zoos to support the survival of threatened shark species and is engaged in broader marine conservation projects, including coral reef protection, which benefits marine biodiversity, including shark habitats. Paul also maintains professional and academic relationships with the European Space Agency (ESA) / ESTEC environment, stakeholders, and several Dutch universities. He has experience in launching and advising both scientific and industry-focused journals and books in the framework of the Sustainable Development Goals, including SDG 14, Life Below Water.

As a volunteer, he also serves as Global Ambassador for Aquaculture without Frontiers (AwF) and as President of the Advisory Council of Seafood Consumers Association Ltd (SCA), which is globally active and established in Australia.

1. Based on your experience in aquaculture and related industries, what do you consider the most pressing challenges and opportunities for sustainable aquaculture development today?

Sustainable development in food security is essential, given the growing global human population. We need to use not only land areas and agricultural surfaces, the 2D surface of the earth, but also the 3D volume of the ocean to produce protein and carbohydrates from fish, crustaceans, and macro- and microalgae; seaweed. Climate change mitigation is essential to maintain the ocean's capacity to absorb greenhouse gases. Due to rising water temperature, fish are migrating, and the ecosystem is changing.

2. How do you see the role of biosecurity and disease management evolving in modern aquaculture systems, and what best practices have proven effective?

Biosecurity is essential for the marine food web. Top predators like sharks maintain the availability of fish for fish feed as well. Biosecurity at the first trophic level, algae, is essential to sustain the marine ecosystem. No algae, no fish (to catch). Disease management in high-productive farming should draw on scientific insights across new domains. Using bioinformatics / computational biology to govern disease in terms of strengthening health, and prevention of disease. Recent developments in strengthening the immune system of the White Leg Shrimp using gene expression is an upcoming practice. Farming the red seaweed species Porphyra using a through-bioinformatics developed multiplication trigger is another practice.

3. In your collaborations with academic institutions and industry, how can research findings be translated more effectively into practical solutions for aquaculture operations?

Through cooperation with farmers, innovative operations can be conducted transparently. This is a conundrum. Understanding and respecting IP and competition, not only in industry but also in academia, is a limitation.

4. What emerging technologies or innovations in aquaculture do you find most promising for improving efficiency, sustainability, and environmental compliance?

Bioinformatics/computational biology to disclose biochemical mechanisms and understand biological and physiological opportunities.



5. How can the aquaculture sector contribute to global food security while minimizing its environmental footprint?

Taking care of the ecosystems, the food web, and mitigation of the impact of their operation on the environment.

6. From your experience with international collaborations, what lessons can aquaculture managers learn to enhance productivity and sustainability in local and global contexts?

Communication, communication, and communication with a wide range of stakeholders and their interests.

7. As someone experienced with scientific publishing, what strategies would you recommend to increase the visibility and impact of aquaculture research internationally?

Besides publishing in peer-reviewed journals, publish in magazines of interest to stakeholders in language a 12-year-old reader will understand, think of 'Our Common Future', the Brundtland report on sustainable development.

8. Looking forward, what do you think are the key trends and priorities for the aquaculture industry over the next decade, particularly in Europe?

Key trends and priorities for the







aquaculture industry in Europe over the next decade include significant growth driven by rising seafood demand, sustainable production practices, and technological advancements. The market is expected to grow at a compound annual growth rate (CAGR) of around 5% to 5.1% from 2025 to 2035, reaching an estimated value of up to USD 191 billion. This growth is supported by consumer preferences for locally sourced and eco-friendly seafood, government policies focusing on sustainability, and increasing investments in disease control and controlled farming environments to improve fish health and welfare.

Sustainability is a central priority, with efforts addressing environmental impacts such as nutrient discharge and promoting low-impact feed ingredients as alternatives to wild fish stocks. There is a strong focus on climate change adaptation, energy transition, and integrating sustainable aquaculture into broader EU food and environmental strategies. Regulatory reform to simplify licensing and allow more flexible, science-based approaches is critical to driving innovation and resilience in the sector. Key initiatives also include advancing research into selective breeding, novel health strategies, and development of new, environmentally friendly feed additives.

Another priority is improving animal welfare standards, supported by new EU research projects and platforms promoting best practices across aquaculture operations. Expanding sustainable aquaculture production in freshwater, marine, and land-based systems such as Recirculating Aquaculture Systems (RAS) and Integrated Multi-Trophic Aquaculture (IMTA) is encouraged to enhance production diversity. Alongside technological innovation, the aquaculture sector aims to maintain competitive market conditions through clear labeling, traceability, and safeguarding sustainability standards relative to imports.

Important industry players in Europe drive innovations in sustainable feeds, fish health, and farming technologies. In addition, the importance of gaining social license and ecosystem service recognition for aquaculture, emphasizing human capital development and lifelong learning for sustained sector growth.

In summary, Europe's aquaculture industry for the next decade prioritizes sustainable growth, climate resilience, regulatory reforms, technological innovation, and social acceptance to meet increasing seafood demand while minimizing environmental footprint and ensuring high animal welfare standards.

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PHOTO 1. Riverine fishers with a managed pirarucu catch, Mamirauá Sustainable Development Reserve, Brazilian Amazon. Photo: Aline Fidelix.

Pirarucu: Two Bets on One Amazon Giant

Wild-managed or farmed, the Amazon's largest fish is quietly making the economic case for its own conservation.

There's a fish in the Amazon that has to surface for air every few minutes — either the worst evolutionary decision in freshwater biology, or the reason it's still here at all. The pirarucu (Arapaima spp.) breathes atmospheric oxygen through a primitive, lung-like organ, letting it survive in stagnant, oxygen-poor backwaters where most fish would give up (Castello, 2008). At over 3 metres and 200 kilograms, it is also one of the largest freshwater fish on the planet, and for centuries it has sustained the food culture of Indigenous and riverine communities across the Basin. Then, for most of the twentieth century, it nearly disappeared — because a fish that has to surface to breathe is easy to spear (Castello, 2008; Castello, Viana, Watkins, Pinedo-Vasquez, & Luzadis, 2009).

By the 1990s, pirarucu was overfished to scarcity across much of its range (Castello et al., 2009). What has happened since is one of the best conservation stories in Amazonian resource management — and it has produced two very different production systems that anyone watching Amazonian aquaculture should have on their radar.

The comeback: managed, not just protected

The first pathway isn't aquaculture at all — it's a community-management model, worth understanding even for readers who care only about farmed fish, because it sets the bar for what "sustainable Amazonian pirarucu" is now expected to mean. Under government-authorised management plans, riverine and Indigenous communities conduct annual population counts (pirarucu obligingly surface to breathe, making them countable in a way most fish aren't), set harvest quotas based on those counts,

and collectively govern the whole system. It is a working piece of social infrastructure that took decades to build, combining traditional ecological knowledge with formal science and public institutions (Silva et al., 2020; Gonçalves & Santos, 2024).

The scale is hard to grasp. The state of Amazonas alone now has more than 15.1 million hectares of specially protected areas under pirarucu management (IBAMA, 2024) — roughly the size of England or Nepal. Populations that crashed a generation ago have recovered (Castello et al., 2009; Silva et al., 2020; Gonçalves & Santos, 2024). The less-told part of the story: the fishery still leaves value on the table, since much of what the market pays a premium for — traceability, provenance, the conservation story itself — doesn't yet flow back proportionally to the communities that generate it.

The farm bet: growing income faster than trees do

The second pathway is aquaculture, where this magazine's readers will feel more at home. Pirarucu farming has been steadily expanding across northern Brazil, mostly among small and medium-scale producers, often alongside tambaqui (Lima et al., 2015; Mesquita et al., 2022). What makes the species interesting as a farmed animal isn't exotic — it's arithmetic. Pirarucu can gain 8–10 kg in its first year, one of the fastest growth rates of any native fish farmed anywhere (Lima, 2020). That growth curve isn't just a production metric; it's a financing tool.

Here's the part that is underplayed: accumulated deforestation has cleared roughly 21% of the original Brazilian Amazon forest cover — about 88 million hectares, larger than France and the United Kingdom combined, most of it now low-productivity cattle pasture (Science Panel for the Amazon, 2021; MapBiomas, 2024). Bringing even a fraction of that land back into regenerative use through agroforestry is a massive, largely untapped opportunity. The problem has never really been biological — it's cash flow. Trees take three to eight years to start paying anyone back (FAO, 2025), and farmers weighing that timeline against next month's bills tend to choose the bills. A fish that reaches harvest weight in a single season, farmed on the same converted land, gives a producer income while the trees are still finding their feet. Pirarucu, in other words, may be less a fish product than a bridge loan with fins.

That's the optimistic read. The honest read includes the bottlenecks. Reproduction still depends largely on pairs forming naturally and compatibly in the pond — broodstock management remains more art than protocol, and a reliable fingerling supply remains one of the sector's tightest constraints (Lima et al., 2015; Gálvez Escudero & Mendoza De La Vega, 2024), even as molecular sex-identification tools start to give hatcheries better selection data (Adolfi et al., 2021; López-Landavery et al., 2022). Once fish are in the water, feed accounts for around half of production costs (Lima et al., 2015; Pedroza Filho et al., 2016) — the single biggest lever on pirarucu's margins isn't genetics or growth rate at all, it's the feed bag.

Two markets, one shared infrastructure problem

Community-managed and farmed pirarucu aren't really competing for the same buyers. Wild-managed fish trades on story: certification, traceability, and the fact that buying it funds the floodplain conservation that produced it. Farmed pirarucu plays a different game — consistent, scalable supply for domestic and export markets, the kind of volume premium wild fisheries can't provide.

Both systems share a logistics problem neither has solved. Cold chain, processing capacity, transport from



PHOTO 2. Pirarucu scales, prized in the leather trade. Photo: Aline Fidelix.



remote Amazonian regions, and market coordination cap value creation for wild and farmed products alike — which is why a fish that can sell at premium prices still leaves so much value stranded upstream of the consumer. Beyond the fillet, there is real money in co-products the sector has barely begun to monetise at scale: pirarucu leather already commands strong prices, while collagen, fishmeal, and oil extraction remain largely untapped. None of that gets built without patient capital and coordinated investment across the value chain — public, private, and impact.

Not rivals — two answers to the same question

It's tempting to frame community fisheries and aquaculture as competing models — wild versus farmed, tradition versus industry. That framing misses what's actually happening. Community-managed pirarucu is already an established conservation success, recovering wild populations and protecting floodplain ecosystems while sustaining community livelihoods and governance. Aquaculture adds another possibility: small- and medium-scale producers, organised through cooperatives and producer associations, can strengthen rural livelihoods, food and nutrition security, and local food systems while producing a native species with substantially lower land requirements and greenhouse-gas emissions than cattle (Pacheco et al., 2025). Integrated with agroforestry on already converted pasture, pirarucu farming could help regenerate landscapes and diversify rural incomes. Because pirarucu is deeply rooted in Amazonian food culture, producing a local species also strengthens the connection between food systems, biodiversity, and cultural heritage (Burlingame & Dernini, 2012). As demand for animal protein grows, responsibly farmed pirarucu can help meet part of that demand through a species that already belongs to the Amazon.

Future instalments in this series will delve into the specifics — certified fillet export requirements, the leather and by-product value chain, cold-chain logistics, gastronomic market demand, and where impact capital fits in scaling this properly. There is plenty of runway left on this fish.

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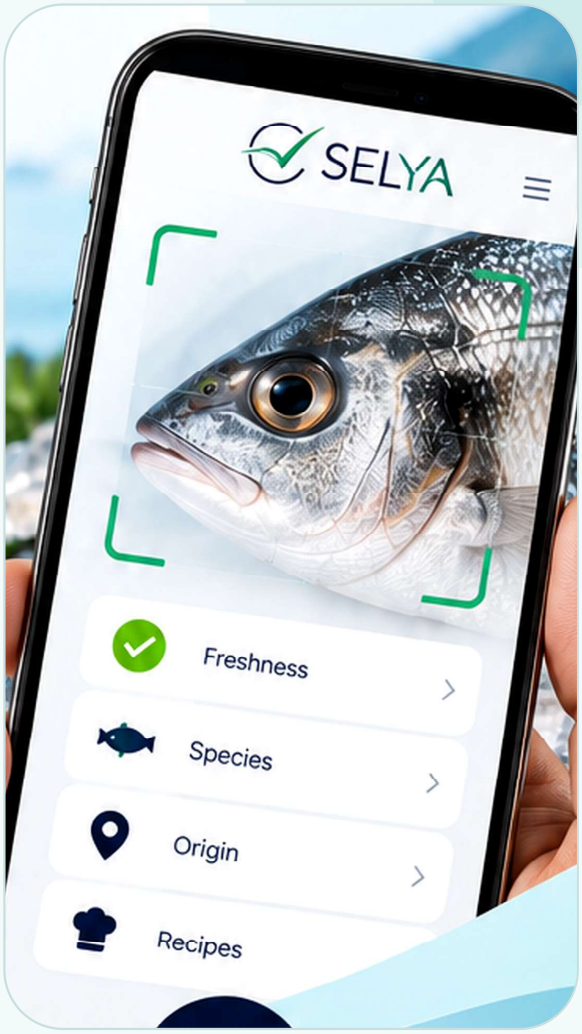
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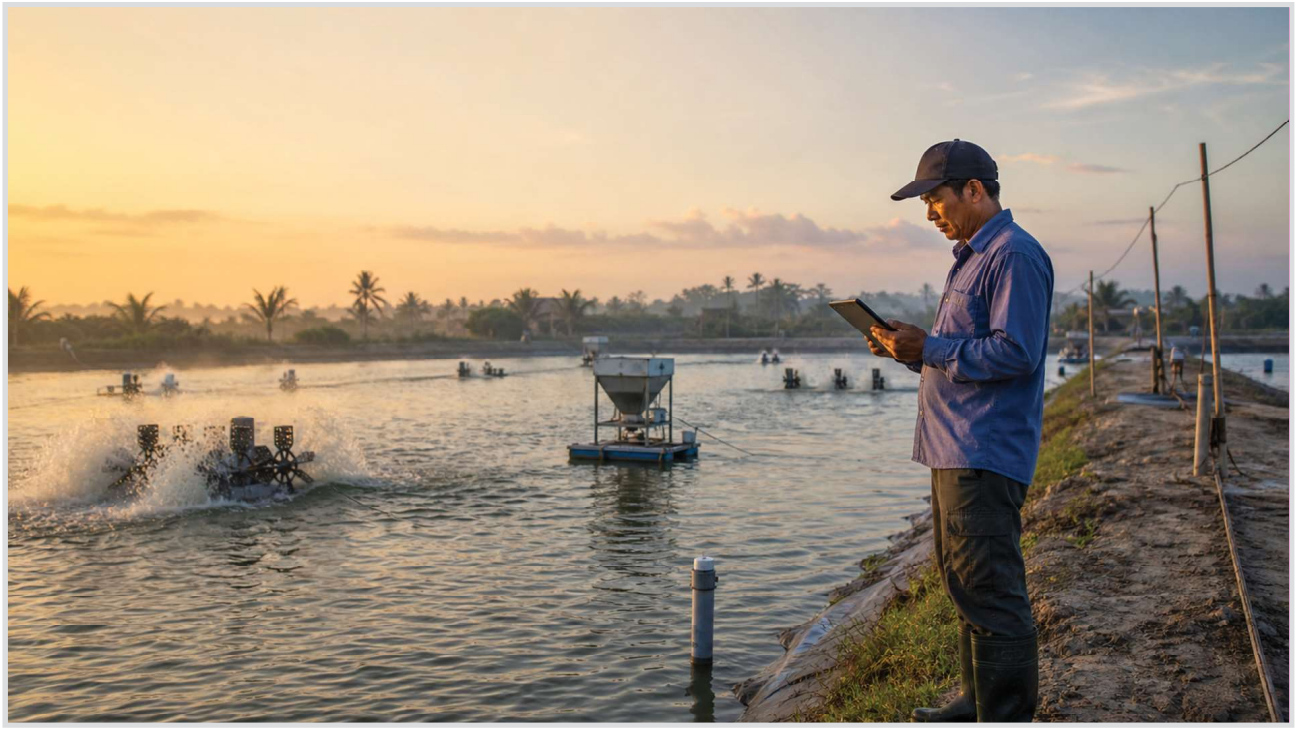
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Aquaculture 4.0: Turning Biological Uncertainty into Bankable Growth

Aquaculture has proved it can grow fish and shrimp. Now it must prove it can grow confidence.

That distinction matters. The sector has made extraordinary advances in genetics, nutrition, health management, farm design and production technology. In 2022, aquaculture surpassed capture fisheries as the principal source of aquatic animals. Yet capital still approaches much of the industry cautiously. Insurance remains uneven. Many farms that are technically sound and commercially viable still struggle to finance the equipment that would make them more productive, resilient and sustainable.

The contradiction is easy to see: performance has improved, but uncertainty has not fallen at the same pace.

After nearly three decades working across farms, academia, consulting, government and international industry leadership, I have reached a clear conclusion. Aquaculture's next constraint is not biological potential. It is system design. We continue to improve individual components while leaving the production and financial ecosystem fragmented. Better feed cannot deliver its full value without better feeding decisions. Sensors cannot transform a farm if their data remain isolated. Finance cannot scale when lenders cannot see how biological risk is developing during the cycle.

This is the purpose of Aquaculture 4.0: not digitalisation for its own sake, but digitalisation for operational control, bankability and insurability.

Aquaculture is a living production system. Dissolved oxygen changes by the hour. Feeding response shifts with temperature, biomass, weather and animal health. Growth curves can move away from plan long before the deviation becomes obvious. In many farms, however, decisions are still made from periodic sampling, delayed records and personal experience.

Experience will always matter. But experience without continuous visibility forces even excellent producers to manage reactively.

This is the industry's "black box" problem. We know the inputs and eventually measure the outputs, but much

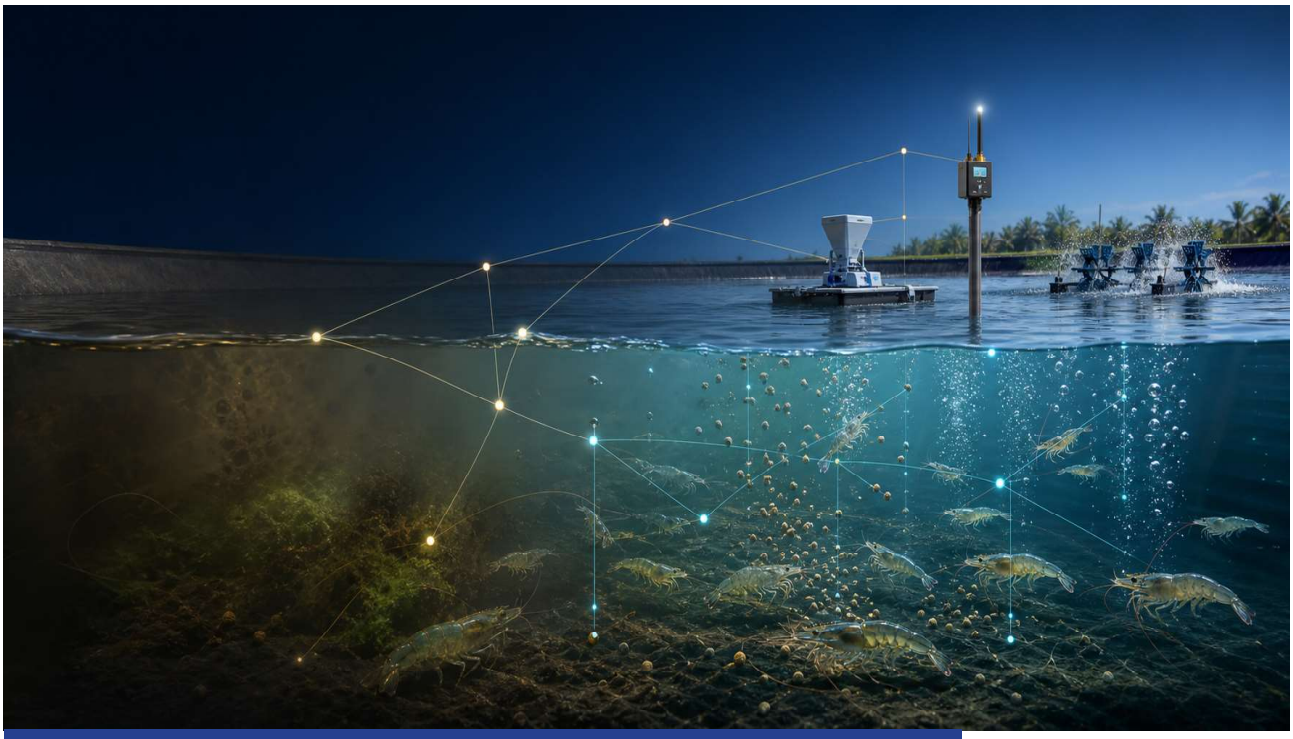


Figure 1. A shrimp-pond cross-section moves from darkness and unobserved biomass at left to visible oxygen, feeding activity, sensors and connected data at right. It visualises the article's "black box": the hidden interval between stocking and harvest that telemetry turns into measurable biological performance and financial risk.

of what happens between stocking and harvest remains unseen. When the core process is invisible, biological variation becomes operational volatility. Operational volatility becomes cash-flow uncertainty. Cash-flow uncertainty becomes expensive credit, restricted insurance or no capital at all.

Capital does not require zero risk. It requires knowable risk.

That is why the same information that helps a farmer prevent a pre-dawn oxygen crash also matters to a lender. A stable dissolved-oxygen profile is not merely a water-quality record; it is evidence of management discipline and survival probability. A reliable biomass curve is not simply a production metric; it is a forward view of harvest timing and revenue. Consistent feeding behaviour is not just an operational signal; it is an early indicator of biological health and repayment capacity. Figure 1 makes this relationship visible by showing how telemetry turns the hidden production interval into measurable biological performance and financial risk.

I describe Aquaculture 4.0 through three pillars: infrastructure, data and systems integration. Their value lies in how they work together. Figure 2 maps how these pillars convert farm signals into verified information that can be shared across the production and financial ecosystem.

Infrastructure is the ability to see and act. Digital infrastructure includes dependable connectivity, rugged sensors, edge devices for low-bandwidth environments, secure cloud systems and farm-management tools. Physical infrastructure includes automatic feeders, aeration, reliable power, biosecurity upgrades, harvesting equipment and cold-chain capacity. We cannot digitise thin air, and an alert has little value if the farm lacks the equipment or operating protocol to respond.

Data is the language of risk. The industry needs timely, standardised and longitudinal information covering water quality, feeding, biomass, survival, feed conversion, health, energy use, traceability and cost structure. But volume is not the objective. Data must answer four basic questions: who recorded it, what was measured, when and where did it occur, and can a third party verify it? Only then do readings become decision-grade intelligence.

Systems integration creates one version of the truth. A single sensor does not make a smart pond, and a smart pond does not make a bankable enterprise. Information must flow among farm systems, hatcheries, feed mills, laboratories, processors, buyers, insurers, regulators and financial institutions. When these actors work from compatible information, compliance can be automated, performance can be benchmarked and risk can be monitored throughout the production cycle rather than reconstructed after something goes wrong.

Together, the three pillars create a managed biological system: infrastructure allows us to see risk, data allows us to measure it, and integration allows us to manage and share it.

Producers sometimes hear "more data" and understandably imagine more administration. Aquaculture 4.0 should produce the opposite result. Good digital systems reduce manual reporting while giving the farmer stronger evidence in every commercial conversation.

Feed typically represents the largest share of operating cost in intensive finfish and crustacean production. When feeding is aligned with appetite, biomass and oxygen

availability, small improvements in feed conversion compound across the farm. Less feed is wasted, organic loading falls, oxygen becomes more stable, growth is more uniform and harvest forecasts improve.

A bioeconomic model of a commercial shrimp farm in Mexico illustrates the scale of the opportunity. Moving from manual feeding to automation reduced the modelled feed conversion ratio from 2.08 to 1.88 and increased production by about 15 per cent. Adding hydrophones and real-time telemetry reduced the ratio further to 1.64, while substantially improving output and profitability. Feed-related carbon intensity fell by an estimated 21 per cent against the baseline.

The precise result will vary by species, farm and environment. The strategic lesson does not: better control can improve profitability and environmental performance simultaneously, and continuous records make that improvement visible to others.

For the farmer, visibility becomes bargaining power. It can support longer loan tenors, lower rates, stronger buyer contracts and insurance designed around actual operating conditions rather than broad assumptions. The conversation moves from "trust me" to "verify me".

Traditional agricultural credit is often built around land collateral and predictable seasonal cycles. Aquaculture does not fit neatly into that architecture. Biological assets are dynamic, production can be continuous and the most important risks unfold underwater.

Digital infrastructure makes a different model possible. Automated feeders, aerators and monitoring systems are not only production equipment; they can become financeable assets. They are modular, recoverable and redeployable. Telemetry shows whether they are being used, whether the farm is stable and whether performance is beginning to drift. Repayment can be aligned with harvest rather than an arbitrary calendar, while early-warning signals allow technical intervention before operational stress becomes financial distress.

Insurance can also move from retrospective compensation to active risk management. Parametric products can use agreed environmental triggers (such as sustained oxygen or temperature stress) to release liquidity while farms are still operating. That money can keep aeration running, maintain feeding discipline and protect debt service before a shock becomes a terminal loss. With reliable, timestamped data, claims are faster, disputes are fewer and risk can be priced at farm or cluster level.

This is an important change in mindset. Finance and insurance should not sit outside the production system, waiting for the result. Properly designed, they become part of the infrastructure that stabilises it.

The same visibility that supports credit also changes the sustainability conversation. Feed conversion, dissolved-oxygen stability, nutrient discharge, energy use, carbon intensity, water performance and traceability can increasingly be measured rather than asserted.

That matters because blue finance and sustainability-linked capital depend on evidence. A farm or cluster that demonstrates lower environmental volatility and



Figure 2. From left to right, pond sensors, solar power, aeration and automated feeding capture operating conditions; the signals become structured, verified records; and an integrated network shares the information with the farmer, feed mill, laboratory, regulator, insurer and lender. The sequence directly represents the article's three pillars: infrastructure, data and systems integration.



Figure 3. Clockwise from the instrumented pond, operating data feeds risk analysis; clearer risk assessment supports finance; finance enables feeder and aeration upgrades; and those upgrades produce more stable farming and richer data. The five-stage loop illustrates the article's data-finance flywheel and explains why adoption can become self-reinforcing.

improving resource efficiency can be rewarded through better lending terms or insurance pricing. Environmental performance lowers risk; lower risk reduces the cost of capital; better capital terms make further environmental investment possible.

Sustainability, in other words, is not a separate layer added for reporting. It is the outcome of a well-managed system and a financial signal in its own right.

Once continuous information enters the system, a powerful cycle begins:

Data improves risk assessment. Better risk assessment unlocks finance. Finance accelerates technology adoption. Adoption generates more and better data. Figure 3 presents this sequence as a self-reinforcing data-finance flywheel.

This data-finance flywheel creates value for every participant. Farmers gain control and access to capital. Feed mills improve demand forecasting, technical service and credit allocation. Governments gain earlier visibility into disease and environmental drift. Buyers receive stronger traceability. Lenders and insurers build portfolios around measured performance rather than generic perceptions of sector risk.

Across the industry, the task now is to connect sensors, feeding systems, satellite information, environmental intelligence and financial analytics through interoperable architectures. The objective must be larger than farm efficiency. It is to create scalable, financeable production systems at industry level while allowing farmers to retain agency over their data and share verified information with the institutions that need it.

The countries that move first will gain more than a technological advantage. They will accumulate the multi-cycle data, institutional capability and financial relationships that define the next era of aquaculture. The same is true for companies and capital providers. Early participants will learn faster, price risk more accurately and build trust that late entrants cannot reproduce overnight.

Aquaculture does not need another disconnected revolution. It needs to connect what we already know, prove what we already do and finance what already works.

The progression is straightforward: when we can see the system, we can understand it. When we understand it, we can manage it. When we manage it, we can finance it. And when we finance it, we can finally scale it with confidence.

That is Aquaculture 4.0. That is the last mile of growth.

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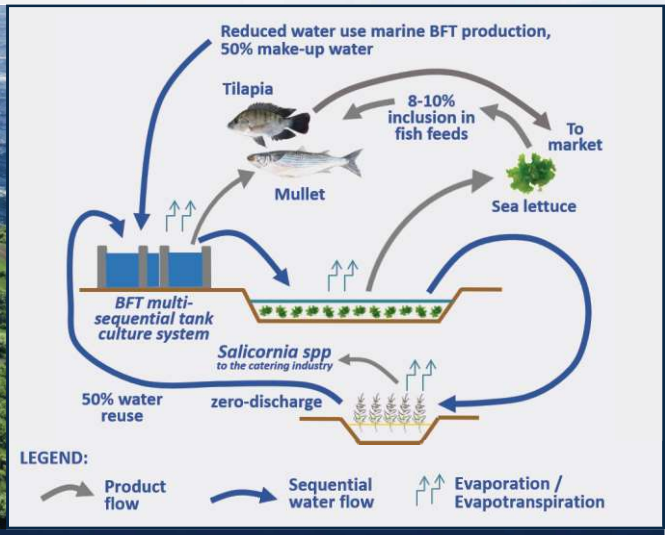
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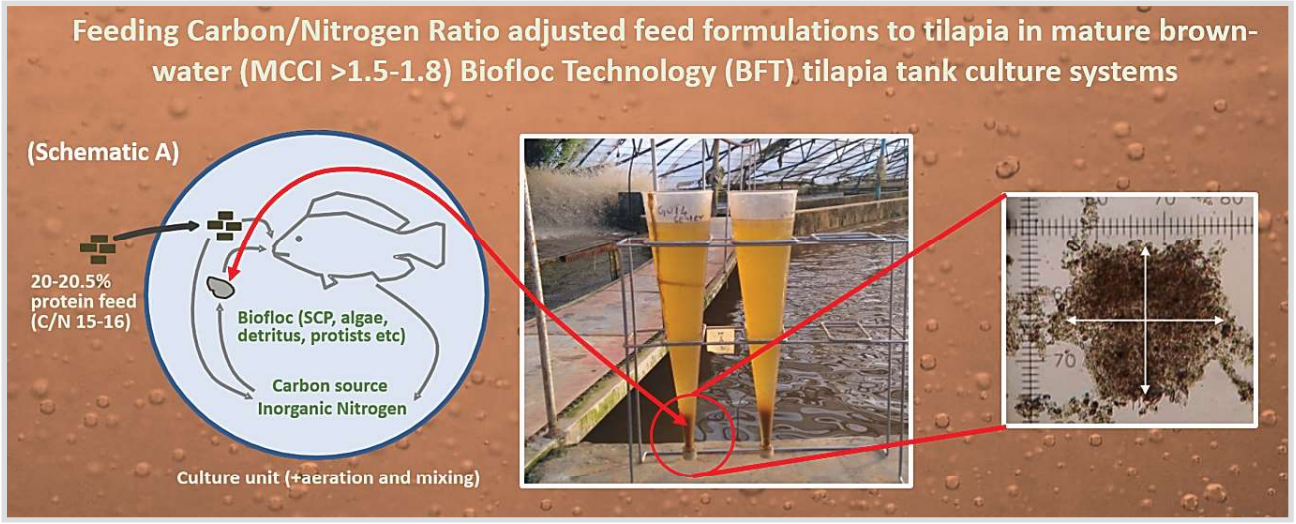
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Feeding Tilapia in Biofloc Technology (BFT) Tank Systems: C/N Ratio Management through Feeding Practices

Introduction

Biofloc Technology (BFT) is a sustainable aquaculture method that simultaneously improves water quality, helps suppress harmful pathogens, and generates value-added microbial protein within the culture system. Tilapia and shrimp are particularly well suited to BFT because their ability to consume microbial floc allows part of their nutritional requirements to be met from the culture environment, reducing reliance on formulated feed.

Despite these advantages, feeding remains one of the less clearly understood aspects of tilapia BFT production. Practical uncertainty commonly concerns feeding rates, carbon management, and the choice between two approaches: (1) conventional feed supplemented with an external carbon source, and (2) a C/N-adjusted, feed-integrated strategy in which the carbon requirement is incorporated into the feed.

These approaches are not contradictory: both seek to establish a carbon-rich environment in which heterotrophic microorganisms assimilate inorganic nitrogen and produce biofloc. The important difference is where the carbon enters the production system and how its energy is initially allocated. This article clarifies that distinction and uses bioenergetics-based worked examples, calibrated against observations from large-scale commercial BFT tilapia production, to examine the implications for feed use, oxygen demand, carrying capacity and harvest yield.

Particular attention is given to mature (>4-month-old) brown-water BFT systems with Microbial Community Colour Index (MCCI) values approximately >1.5 and <1.8, where the contribution of established biofloc to fish nutrition becomes increasingly relevant due to increased floc protein content.

The role of carbon as a control element in BFT tilapia tank systems

In Biofloc Technology (BFT), the carbohydrate addition (ΔCH) required to assimilate the ammonium flux into microbial protein can be calculated following Avnimelech (1999):

$$\Delta CH = \frac{\text{Feed} \times \%N_{\text{feed}} \times \%N_{\text{excretion}}}{0.05}$$

This formula allows estimation of the effective C/N ratio or the equivalent protein concentration of the feed. Worked Example: Assume feed pellets containing 30% protein (4.65% nitrogen, based upon N X 6.25), with 50% of feed nitrogen excreted. Substituting into the equation:

$$\Delta CH = \frac{\text{Feed} \times 0.0465 \times 0.5}{0.05} = 0.465 \times \text{Feed}$$

Thus, a 30% protein feed requires supplementation with 46.5% carbohydrate (low protein, low N). The corrected protein concentration becomes:

$$\text{Corrected Protein \%} = \frac{30}{1.465} = 20.48\%$$

Correspondingly, the C/N ratio rises from 10.75 (original feed) to 15.75 after carbohydrate amendment. See Figure 1.

Avnimelech (1999) assumes that all feedstuffs contain ~50% carbon which aligns with the broader biochemical framework established by Kerr et al. (2026) indicating that most common feedstuffs (grains, oilseeds, by products) cluster around ~50% carbon when expressed on a dry matter basis.

While, Johan Kjeldahl, the Danish chemist and brewer demonstrated that proteins consistently contain ~16% nitrogen. This discovery led to the protein constant (often called the Jones factor), expressed as:

"Crude Protein"="Nitrogen"×6.25

This conversion factor (16% = 1/6.25) has been widely adopted due to its applicability across meats, dairy, fish, and fish by products (Greenfield & Southgate, 2003) as used by Avnimelech (1999) to estimate N from protein content.

Two routes to a target C/N ratio

A target feed C/N ratio of approximately 15–16:1 can be established in BFT tilapia systems in two principal ways. In the feed-integrated approach (Schematic A), a lower-protein, C/N-adjusted feed incorporates the additional carbon within the feed itself. In the supplemental-carbon approach (Schematic B), a conventional higher-protein feed is used and an external carbon source, such as molasses, ground maize or sorghum etc. is added directly to the culture water. See Figure 2.

Both approaches promote heterotrophic microbial growth. The resulting microorganisms assimilate inorganic nitrogen, become part of the biofloc complex, and can subsequently be consumed by tilapia. The process therefore creates an internal nutrient-recycling pathway in which dissolved inorganic nitrogen is converted into microbial biomass and returned to the fish as a supplementary food resource.

The fundamental distinction is the initial destination of the carbon. In the feed-integrated strategy, digestible feed-derived carbon is first available to the fish as dietary energy, while residual and excreted carbon supports microbial processes. In the supplemental-carbon strategy, the added carbon is introduced primarily as a microbial substrate and is initially metabolised by the heterotrophic community. A proportion of the resulting microbial biomass may later be recovered by fish consumption of biofloc.

This difference does not mean that supplemental carbon is inherently 'lost'. Rather, it represents a different allocation of carbon and energy within the fish–microbial system. The feed-integrated strategy potentially provides a more direct carbon-to-fish pathway while simultaneously supplying carbon for microbial nitrogen assimilation.

Production and bioenergetic implications

Practical observations from Chambo Fisheries, Malawi, provide an important indication of the potential difference between the two approaches. An FCR of approximately 1:1 was achieved with a 20.2% protein feed (Digestible Energy (DE) of 11.25MJ/kg as-fed) consistent with the feed-integrated C/N strategy, compared with approximately 1.9:1 when conventional feed was combined with molasses (64% carbohydrates) fed to the tank culture water and the carbon source was included in the FCR calculation. These observations are farm-specific and are not controlled experimental evidence of causality, but they provide a useful practical basis for examining the underlying mechanisms.

A further consideration is the nutritional contribution of mature biofloc. Gallardo-Collí et al. (2019) documented substantial changes in the microeukaryote community and biofloc composition during a 25-week

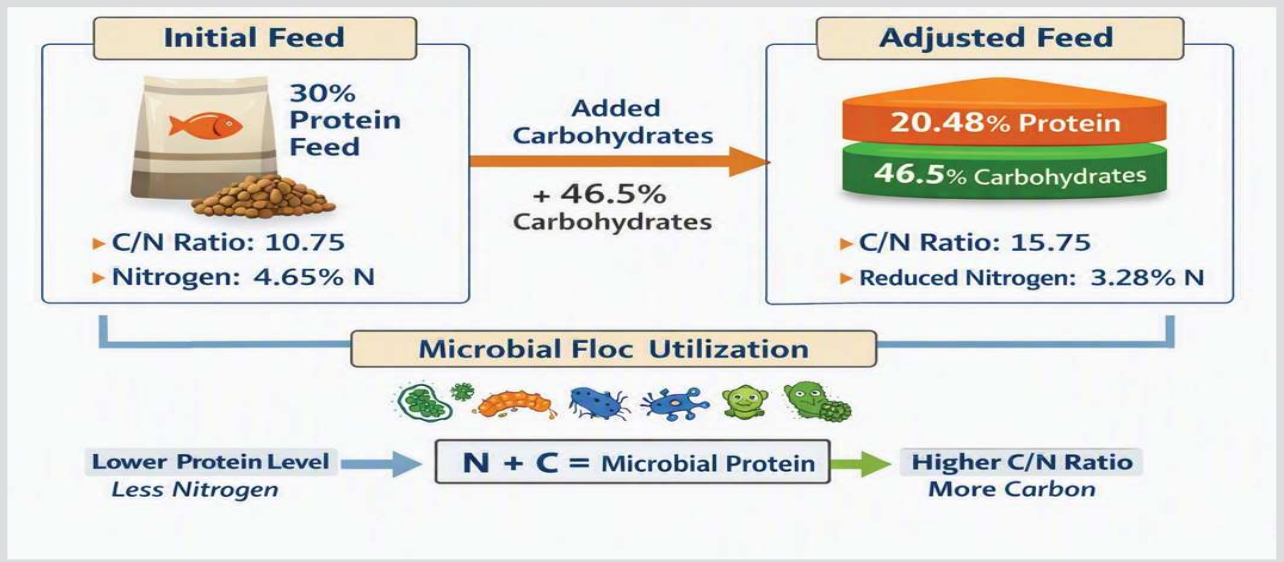


Figure 1: Worked exam[le outputs for a 30% protein feed (4.65% N), C/N ratio 10.75 after carbon source addition to reach C/N ratio of 15.75

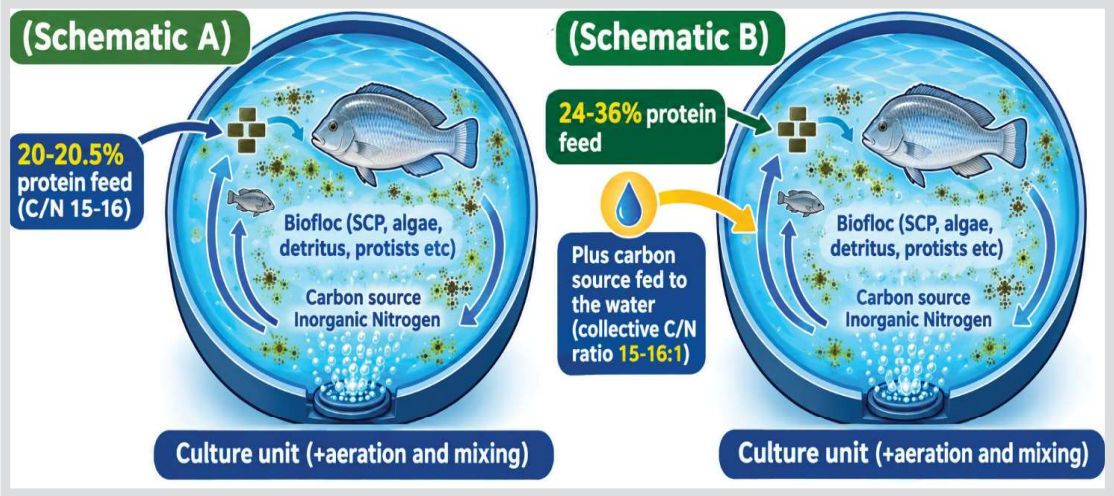


Figure 2: Supplemental Carbon Feeding to the Culture Water (Schematic B) or C/N Ratio Adjustment Through Feed (Schematic A)

Nile tilapia culture experiment, with biofloc protein reaching approximately 47% of dry matter and lipid declining to approximately 2–3% toward the end of the study. Consequently, the nutritional value of a 20–20.5% protein feed in mature BFT should not be assessed in isolation from the additional protein, amino acids and other nutrients supplied through biofloc consumption.

This also supports the use of bioenergetics-based models for feed allocation or daily Feed Allotment (dFA). When carbon is integrated into the feed, the same measured ration supplies dietary energy to the fish while establishing the carbon availability needed for microbial nitrogen assimilation. Feed therefore functions both as a nutritional input and as a mechanism for controlling the microbial C/N balance.

At Chambo Fisheries, production inventories from six 766-m^3 grow-out tanks over approximately three years (2013–2017) indicated a practicable operational feed-loading limit of approximately 0.3 kg feed/m^3/day, based on observed relationships among feed input, fish growth, FCR and aeration energy consumption (Kourie, 2017 a, b, c). This illustrates that feed loading in BFT cannot be considered solely as a fish-nutrition variable; it is also a microbial and oxygen-demand variable.

Why supplemental carbon may reduce production under a fixed loading constraint

External carbon added directly to the culture water increases the substrate available for heterotrophic growth and therefore increases microbial oxygen demand associated with assimilation, respiration and maintenance. Where aeration capacity is fixed, this additional demand becomes part of the system's overall oxygen budget and may constrain practical feed-loading capacity.

Assuming a BFT tilapia tank system is designed around a total loading limit of approximately 0.3 kg/m^3/day, adding external carbon means that part of this loading consists of a carbon source that is not initially directed toward fish nutrition. The carbon is first processed by the microbial community, after which some of the resulting microbial biomass may become available to the fish through biofloc consumption.

The potential yield disadvantage is therefore best understood as an oxygen (loading, aeration) - and energy-allocation (digestible energy) issue rather than simply as carbon loss. The relative efficiency of the two strategies will depend on carbon-source characteristics, digestibility, microbial biomass production and consumption, oxygen availability, aeration capacity, feed loading and overall culture conditions.

Worked example: feed loading and projected harvest yield

Basis of comparison

A 100-m^3 batch BFT tilapia system is modelled at a design loading limit of 0.3 kg of input per m^3 of tank volume per day. Both strategies are evaluated over a 126-day production cycle at 27°C. The model assumes stocking with 15.9-g fingerlings, a final fish weight of approximately 425.3 g, equal feed energy density of 11.85 MJ/kg as-fed, and an equivalent Natural Food Contribution factor (NFCf) of 0.20 (20%) for both strategies.

Daily feed allotment is calculated from the theoretical digestible-energy requirement of the fish, adjusted for the 20% contribution attributed to natural food/biofloc (NFCf) consumption

$$dFA = \frac{W_i \cdot TDEN \cdot (1 - NFC_f)}{DE}$$

Where: TDEN: Theoretical Digestible Energy Need which is the amount of digestible energy (Megajoules, MJ) needed to yield 1kg of biomass gain in tilapia as a function of fish size; Wi = Weight Increment; DE : Digestible Energy available in the feed fed as-fed in Megajoules/kg; NFCf: Natural Food Contribution factor, from 0 – 1 (0=0%, 1=100%) which then accounts for that portion of TDEN contributed by floc harvesting in Biofloc Technology (BFT) tank systems found by deduction from inventory taking (Kourie, 2017 b). Data presented by Chowdhury et al. (2013) enabled

the generation of the relationship between fish size and digestible energy requirements in Megajoules to yield 1kg of biomass gain in tilapia viz. TDEN = 0.009 × BW + 12.45 (R2 = 0.984) calculated by Kourie (2017b) which provides an estimate of TDEN in Oreochromis niloticus.

For the approximately 421.8-g fish used in the model (the last day of feeding before harvest), this gives a dFA of 3.8388 g/fish/day and a calculated feed-only FCR of 1.097 (FCR = dFA/Wi) before supplemental carbon is considered.

Schematic A — 20% protein C/N-integrated feed

In Schematic A, the carbon required to establish the target C/N ratio (15.6:1) is incorporated into the feed and therefore does not represent a separate carbon loading to the culture water. At a design loading limit of 0.3 kg/m^3/day, the calculated carrying capacity is approximately 78 fish/m^3, each with a projected harvest weight of 425.3 g. This corresponds to approximately 32.9 kg/m^3 of harvest biomass and, for a 100-m^3 tank operated over 126 days, a projected harvest of approximately 3,296 kg per crop cycle.

Schematic B — 28% protein feed plus external carbon

In Schematic B, the same dFA of 3.8388 g/fish/day (feed equal DE of 11.85MJ/kg as-fed) is supplemented with approximately 2.42 g of carbon source/fish/day, according to the carbon-supplementation calculation:

$$\text{Carbon} = \left(\frac{\left(\frac{\%P_{\text{feed}}}{100} \cdot \frac{1}{6.25} \cdot 0.5 \cdot 20 \right)}{f_{\text{CHO}}} \right) \cdot dFA_{\text{per fish}}$$

Where: %P_"feed" : Percentage protein in feed; 6.25: Protein-to-nitrogen conversion factor; 0.5: Carbon fraction assumption; 20: Units of carbohydrate required per gram TAN excreted by the fish for 100% assimilation of TAN by heterotrophic bacteria; f_"CHO" : Fraction of carbohydrate in the carbon source and dFA_"per fish" : Daily feed allowance expressed as grams feed per fish per day.

The combined input is therefore approximately 6.26 g/fish/day. When the 0.3 kg/m^3/day design loading constraint is applied to this combined input, calculated carrying capacity falls to approximately 48 fish/m^3. At the same projected harvest weight of 425.3 g, this represents approximately 20.4 kg/m^3 of harvest biomass, or approximately 2,040 kg of fish from a 100-m^3 tank per 126-day crop. The calculated FCR is 1.097 for feed alone and 1.773 when the supplemental carbon is included in the FCR calculation.

Comparative outcome

Under the model assumptions, the feed-integrated strategy produces approximately 12.5 kg/m^3 more harvest biomass, equivalent to approximately 1,256 kg additional fish per 100-m^3 tank per 126-day crop. Schematic A therefore produces approximately 61.6% more harvested biomass than Schematic B (3,296 kg versus 2,040 kg),

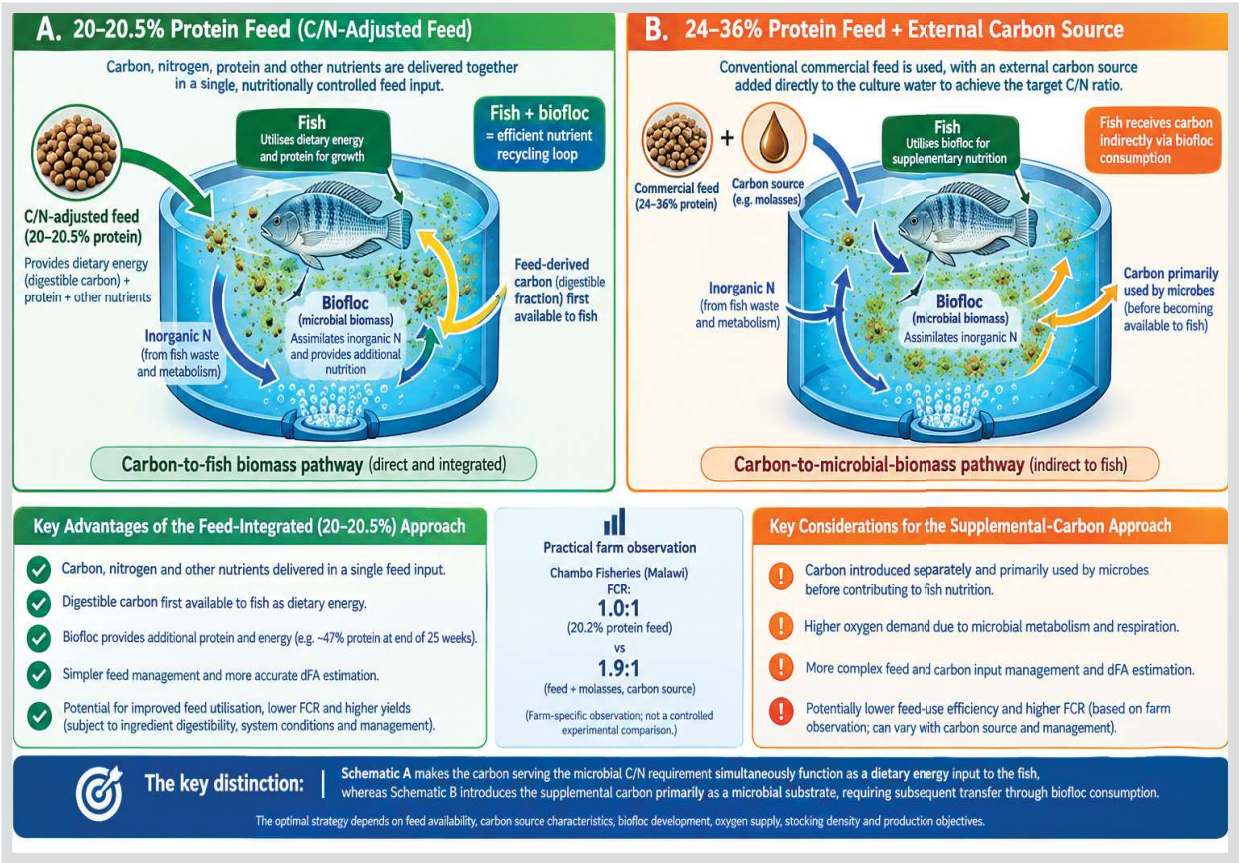


Figure 3: Supplemental Carbon Feeding to the Culture Water (Schematic B) or C/N Ratio Adjustment Through Feed (Schematic A)

Table 1: Comparative outcome of feed loading and projected harvest yields modeling Schematic A — 20% protein C/N-integrated feed vs Schematic B — 28% protein feed plus external carbon

Parameter	Schematic A	Schematic B
Feed formulation	20% protein C/N-integrated feed	28% protein feed + carbon source
Carbon addition to water	None	Yes
Design loading limit	0.30 kg feed/m³/day	0.30 kg feed + carbon/m³/day
dFA	3.8388 g/fish/day	3.8388 g/fish/day
Supplemental carbon	—	2.42 g/fish/day
Total feed input per fish	3.84 g/day	6.26 g/day
Carrying capacity	78 fish/m³	48 fish/m³
Harvest weight	425.3 g	425.3 g
Biomass at harvest	32.9 kg/m³	20.4 kg/m³
100-m³ tank harvest	3,296 kg	2,040 kg
Production cycle	126 days	126 days
FCR	1.097	1.773 including carbon

while Schematic B produces approximately 38.1% less biomass under the same 0.3 kg/m³/day total-loading constraint. See Figure 3.

The calculated FCR is 1.097 for Schematic A compared with 1.773 for Schematic B when the supplemental carbon is included. Thus, the calculated FCR for the feed-integrated strategy is approximately 38.1% ((1.773 – 1.097) / 1.773 × 100 = 38.1%) lower. The 38.1% figure refers to the difference in calculated FCR, whereas the 61.6% figure refers to the difference in projected harvested biomass. They should not be conflated: they describe different aspects of the modelled comparison.

Conclusions from the worked examples

The worked examples are based on empirically derived production data from Chambo Fisheries, a large-scale commercial BFT tilapia farm in Malawi, collected over 2013–2017 (Kourie, 2017 a ,b, c). The comparative calculations are modelled estimates rather than controlled experimental comparisons; nevertheless, the underlying farm observations provide an important practical basis for evaluating the relative production efficiency of the two C/N-management approaches.

Under the assumptions used here, the feed-integrated strategy, using approximately 20% protein feed formulated to a C/N ratio of approximately 15.6:1, gives a projected 61.6% higher harvest biomass and a 38.1% lower calculated FCR than the conventional 28% protein feed supplemented with an external carbon source counted in the FCR calculation. The significance of this result extends beyond the simple difference in protein concentration between the two feeds.

The results support the proposition that mature BFT systems may be relatively protein-rich while remaining comparatively constrained in terms of directly available dietary energy in BFT tilapia tanks. Mature biofloc provides microbial protein, amino acids and other nutrients that supplement the manufactured ration. In such an environment, a conventional 28% protein grower ration may supply more feed delivered protein than is necessary when the contribution of biofloc is considered, while not necessarily optimizing the direct delivery of energy to the fish.

The approximately 20% protein feed-integrated strategy represents a different nutritional philosophy. It reduces manufactured dietary protein level while incorporating sufficient carbon to establish the desired C/N balance. The feed can consequently provide available dietary energy directly to BFT tank cultured tilapia while retaining adequate protein and supplying carbon for heterotrophic assimilation of inorganic nitrogen and biofloc formation. The microbial protein produced in the mature biofloc can then complement the lower-protein manufactured ration. See Figure 4.

This provides a plausible nutritional explanation for why a lower-protein feed can perform efficiently in a mature BFT environment while allowing for higher yields and reduced FCR. The relevant nutritional unit is not the manufactured feed alone, but the combined system of manufactured feed, biofloc-derived protein and amino acids, direct dietary energy and microbial energy pathways. Where mature biofloc contributes substantial microbial protein, the requirement for a high-protein manufactured ration may consequently be reduced, provided that digestible energy, essential amino acids and other required nutrients remain adequate.

Accordingly, feed formulation for mature BFT systems should not necessarily be based exclusively on conventional clear-water aquaculture formulations. The nutritional contribution of biofloc should instead be considered within the overall nutrient and energy budget of the production system. The Chambo Fisheries observations and the worked calculations presented here support the proposition that a C/N-integrated ration of approximately 20% protein may be better aligned with the nutritional environment of mature BFT systems than a conventional 28% protein feed supplemented with external carbon.

MCCI Classification Chart

An Excel-based MCCI (Microbial Community Color Index) Classification Chart has been developed using the closest-fit colors to calculated MCCI values, with corresponding RGB values specified according to Microsoft Office color standards. The chart provides a practical reference for producers and researchers to

estimate MCCI from smartphone photographs of biofloc water. RGB values obtained through AI-assisted image analysis can be entered into the equation, MCCI = (R – B)/(G – B), and the resulting value matched against the classification chart to identify the corresponding biofloc color category and microbial community condition. This approach offers a rapid and accessible field tool for monitoring changes in biofloc development, while direct water-quality and microbial measurements remain necessary for quantitative confirmation. See Figure 5.

Overall interpretation

The central concept can be summarised simply: mature BFT systems may be protein-rich but energy-constrained. A conventional high-protein feed combined with external carbon can therefore provide more formulated feed delivered protein than is required while directing a significant proportion of the added carbon through microbial metabolism before it can contribute indirectly to fish production via floc harvesting. A lower-protein, C/N-integrated feed instead seeks to exploit the complementary roles of feed and biofloc: the feed supplies available dietary energy directly to fish through ingested feed furnishing a good portion of the protein requirement of tilapia while providing the carbon required for microbial nitrogen assimilation; the biofloc supplies the shortfall of additional microbial protein, amino acids and other nutrients.

The implication is that feed formulation for mature BFT systems should not necessarily be based on conventional clear-water aquaculture formulations alone. Instead, the nutritional contribution of the biofloc should be incorporated into the overall nutrient and energy budget of the production system. The observed results from Chambo Fisheries, together with the worked calculations presented here, support the proposition that a C/N-integrated feed, approximately 20% protein ration, may better align the manufactured feed with the nutritional environment of mature BFT systems than a conventional 28% protein feed supplemented with an external carbon source.

Then, within the reported mature BFT system and a MCCI range of approximately >1.5 to <1.8, this feed–biofloc relationship may more closely reflect the combined nutritional and energy requirements of tilapia. See Figure 5. The comparative advantage remains conditional, however, and should be evaluated against the digestibility and energy content of the actual feed,

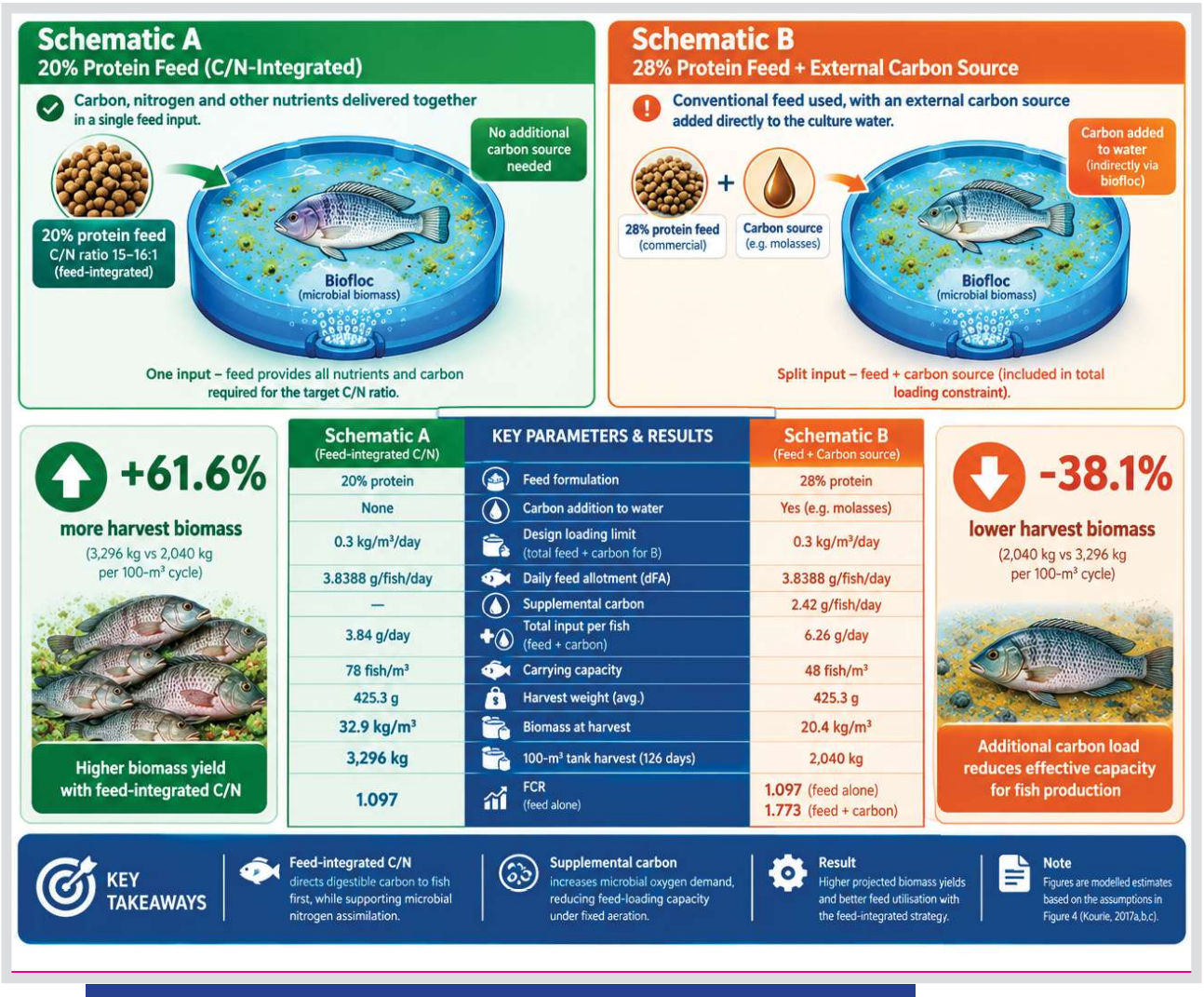


Figure 4: Feed loading and harvest yield comparison in tilapia BFT systems modeling Schematic A — 20% protein C/N-integrated feed vs Schematic B — 28% protein feed plus external carbon

$$MCCI = \frac{(R - B)}{(G - B)}$$

Microbial Community Color Index

Lower MCCI → greener / more photoautotrophic; higher MCCI → browner / more heterotrophic
Use color as a rapid operational proxy alongside DO, TAN, nitrite, alkalinity and direct solids measurements.

MCCI	R	G	B	Hex	Color	Biology	System condition	Management action
0.795	120	137	54	#788936	Bright green	Chlorophytes, diatoms	Immature system	Increase feed loading gradually
0.821	106	123	28	#6A7B1C	Green	Algae dominant	Young biofloc	Maintain C:N inputs and aeration
0.852	101	113	32	#657120	Green	Algae dominant	Young biofloc	Maintain C:N inputs and aeration
0.900	108	116	36	#6C7424	Green	Algae dominant	Young biofloc	Maintain C:N inputs and aeration
0.959	110	113	39	#6E7127	Green	Algae dominant	Young biofloc	Maintain C:N inputs and aeration
1.029	114	112	43	#72702B	Olive green	Algae + heterotrophs	Transition phase	Develop/maintain stable floc; monitor solids
1.072	118	113	44	#76712C	Olive green	Algae + heterotrophs	Transition phase	Develop/maintain stable floc; monitor solids
1.114	123	115	45	#7B732D	Olive green	Algae + heterotrophs	Transition phase	Develop/maintain stable floc; monitor solids
1.155	127	116	45	#7F742D	Green-brown	Mixed consortium	Stable mixotrophic	Maintain current operation; verify DO/TSS
1.186	128	115	45	#80732D	Green-brown	Mixed consortium	Stable mixotrophic	Maintain current operation; verify DO/TSS
1.235	129	113	45	#81712D	Green-brown	Mixed consortium	Stable mixotrophic	Maintain current operation; verify DO/TSS
1.277	129	111	46	#816F2E	Brown-green	Heterotrophic bacteria increasing	Stable biofloc	Production zone; routine DO/TSS monitoring
1.317	130	110	47	#826E2F	Brown-green	Heterotrophic bacteria increasing	Stable biofloc	Production zone; routine DO/TSS monitoring
1.367	130	108	48	#826C30	Brown-green	Heterotrophic bacteria increasing	Stable biofloc	Production zone; routine DO/TSS monitoring
1.439	131	106	49	#836A31	Brown-green	Heterotrophic bacteria increasing	Stable biofloc	Production zone; routine DO/TSS monitoring
1.509	130	103	50	#826732	Light brown	Heterotrophic bacteria increasing	Mature biofloc	Monitor oxygen closely; watch solids
1.564	136	105	50	#886932	Light brown	Heterotrophic bacteria increasing	Mature biofloc	Monitor oxygen closely; watch solids
1.585	136	105	52	#886934	Light brown	Heterotrophic bacteria increasing	Mature biofloc	Monitor oxygen closely; watch solids
1.640	132	100	50	#846432	Light brown	Heterotrophic bacteria increasing	Mature biofloc	Monitor oxygen closely; watch solids
1.700	133	98	48	#856230	Chocolate brown	Proteobacteria/Bacteroidetes dominant	Peak productivity	Begin solids Management; protect oxygen
1.750	130	94	46	#876231	Chocolate brown	Proteobacteria/Bacteroidetes dominant	Peak productivity	Begin solids Management; protect oxygen
1.809	129	91	44	#896334	Chocolate brown	Proteobacteria/Bacteroidetes dominant	Peak productivity	Begin solids Management; protect oxygen
1.848	127	88	42	#8C6233	Chocolate brown	Proteobacteria/Bacteroidetes dominant	Peak productivity	Begin solids Management; protect oxygen
1.907	127	88	45	#7F582D	Chocolate brown	Proteobacteria/Bacteroidetes dominant	Peak productivity	Begin solids Management; protect oxygen
1.951	125	86	45	#7D562D	Chocolate brown	Proteobacteria/Bacteroidetes dominant	Peak productivity	Begin solids Management; protect oxygen
2.000	123	84	45	#7B542D	Chocolate brown	Proteobacteria/Bacteroidetes dominant	Peak productivity	Begin solids Management; protect oxygen
2.056	120	82	46	#78522E	Dark brown	Dense bacterial floc	High carrying capacity	Remove excess solids promptly; reassess loading
2.086	119	81	46	#77512E	Dark brown	Dense bacterial floc	High carrying capacity	Remove excess solids promptly; reassess loading
2.152	118	80	47	#76502F	Dark brown	Dense bacterial floc	High carrying capacity	Remove excess solids promptly; reassess loading
2.212	118	78	45	#764E2D	Dark brown	Dense bacterial floc	High carrying capacity	Remove excess solids promptly; reassess loading
2.250	117	77	45	#754D2D	Darker brown	Aging floc community, high solids	High carrying capacity	Remove excess solids promptly; reassess loading
2.290	116	76	45	#744C2D	Darker brown	Aging floc community, high solids	Overloaded system	Reduce feed loading, remove solids, watch DO
2.333	115	75	45	#734B2D	Darker brown	Aging floc community, high solids	Overloaded system	Reduce feed loading, remove solids, watch DO
2.393	112	73	45	#70492D	Darker brown	Aging floc community, high solids	Overloaded system	Reduce feed loading, remove solids, watch DO
2.444	111	72	45	#6F482D	Darker brown	Aging floc community, high solids	Overloaded system	Reduce feed loading, remove solids, watch DO
2.500	110	71	45	#6E472D	Darker brown	Aging floc community, high solids	Overloaded system	Reduce feed loading, remove solids, watch DO

Figure 5: Biofloc MCCI Classification Guide

carbon source, biofloc development and consumption, oxygen transfer and aeration capacity, feed-loading limits, water quality and farm-specific production conditions.

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From Paper to Practice: Developing SOPs That Work on the Farm Floor

Introduction

Walk into most certified aquaculture facilities, and you will find a binder or a shared drive folder full of standard operating procedures. Ask the staff performing the task described in any given SOP whether they follow it as written, and the honest answer is often no. They follow a version of it: the steps they remember, the order that suits their equipment, the shortcuts that experience has taught them are safe, and the ones it has taught them are not. The document sits in the folder as evidence that a procedure exists, not as the thing staff actually consult when the task is underway.

This gap is rarely visible to those who commissioned the document. An operations manager reviewing a binder of procedures sees completeness: every task covered, every step documented, every certification requirement addressed on paper. What that review does not show is whether the document was ever opened on the farm floor, whether the language matched the reading level of the people using it, or whether the steps, as written, reflect how the equipment actually behaves after a season of operation.

This paper is about closing that gap. It draws on direct experience writing SOPs and delivering adult training across multiple countries, cultures, and literacy levels, including hatchery and farm settings where English was a second, third, or fourth language for most of the staff reading the document. It sets out a practical method for producing documentation that withstands contact with the farm floor, built around five questions that recur constantly in this work: who is actually going to read this, when will they read it, what happens if they only read the first paragraph, what happens if two people read it differently, and what happens six months from now when the equipment or the process has changed.

None of what follows requires new software, new certification frameworks, or additional headcount. It requires a different starting assumption about who the document is really for, and a willingness to test that assumption against what staff actually do, rather than what the org chart assumes they do.

Why Most SOPs Are Written for Auditors, Not Staff

Certification programmes require documented procedures, and the fastest way to meet that requirement is to write documents that read well to an auditor: comprehensive, formally worded, and covering every conceivable variation of a task. That same thoroughness often renders the document unusable in daily practice.

An SOP written to demonstrate control to an outside reviewer and one written to guide a staff member through a task under time pressure are different documents with distinct design requirements. The auditor reads in a quiet office, with time to cross-reference the procedure against a checklist, and no immediate consequence if a sentence takes three readings to parse. The staff member stands at a tank at five in the morning, with wet hands, a batch of larvae waiting, and a supervisor who wants the task finished before the next one

starts. Conflating these two readers and writing a single document to satisfy both is the most common reason SOPs are ignored.

This conflation happens for understandable reasons. Certification audits are periodic and visible; the consequences of failing one are immediate and quantifiable, in the form of a corrective action notice or the loss of the certificate. The daily cost of an unusable procedure is diffuse: a slightly higher mortality rate here, a slower training cycle there, a workaround that quietly becomes the real procedure while the written one gathers dust. Because the audit cost is concentrated and visible, while the usability cost is distributed and invisible, documentation tends to drift towards the auditor's needs by default, unless someone deliberately designs for the other reader as well.

The fix is not to write two entirely separate documents for every task, which doubles the maintenance burden and invites the two versions to drift apart. It is to write one document with a layered structure: a short, usable core that staff actually work from, with the fuller regulatory and technical detail that satisfies certification requirements held in a linked reference section or appendix that the auditor can consult without it cluttering the working procedure. This approach is expanded on later in this paper, in the discussion of a practical template.

Structuring a Procedure Around How Staff Actually Work

Staff rarely read a procedure from start to finish before beginning a task. They glance at it, start the task, and refer back to it when something is unclear or unusual. This is not a failure of diligence; it is how skilled adults approach a familiar task under time pressure, and it is consistent across hatchery and farm settings where this pattern has been observed directly. An SOP structured as a narrative paragraph works against this behaviour, because a reader who glances at a paragraph mid-task has to re-read from the beginning to find their place. An SOP structured as a short, numbered sequence, with the critical steps visually distinct from the routine ones, works well: the reader can locate step six at a glance without re-reading steps one through five.

Observing how a task is performed on-site before writing the procedure produces a structure that better matches the real workflow than starting from a generic template and asking staff to adapt their work to fit it. This observation step is often skipped, particularly when a procedure is adapted from a sister facility, a corporate template, or a previous employer's documentation, because it seems redundant: the task is already being performed, so why observe it before writing it down? The answer is that the order in which a task is written often differs from the order in which it is actually done, especially when equipment quirks, water chemistry, or local supply constraints have shaped a workaround that never made it into any document.

A short list of structural habits recurs across procedures that hold up on the floor. Steps are numbered, not bulleted, so a supervisor can say "we stopped at step four" and be understood immediately. Each step describes one action, not two or three chained together with "and" or "then," because a compound step is most likely to have half of it skipped under time pressure. Anything with a safety, quality, or biosecurity consequence, such as a checkpoint that must be verified before the next step proceeds, is visually flagged, whether by bolding, a symbol, or a shaded box, so it cannot be skimmed past along with the routine text around it. The document states, near the top, in one sentence, what the procedure is for and when it applies, so a reader with the wrong document in hand realises it within seconds rather than partway through the steps.

Writing for Varying Literacy and Language Levels

Aquaculture operations frequently employ staff with a wide range of first languages, literacy levels, and prior technical exposure. A procedure written in dense technical English, however precise, is only useful to the subset of staff who can comprehend it fluently under time pressure. In many hatchery settings, that subset is a minority of the people actually performing the task. A document that reads perfectly well to the manager who wrote it can be functionally inaccessible to the technician who most needs it.

Writing for this reality does not mean sacrificing precision, nor does it mean writing down to staff, an impression that understandably makes some technical authors resistant to the idea. It means favouring short sentences, consistent terminology, and visual aids such as photographs or simple diagrams over long prose, and testing draft procedures with the staff who will actually use them before finalising the document. A parameter such as a target dissolved oxygen range is just as precise when stated in a short sentence with a number as when buried in a paragraph of qualifying clauses; the number does not become less accurate by being easier to find.

Consistency of terminology matters more than variety in this context. A procedure that calls the same piece of equipment a "skimmer" in one step and a "protein





skimmer unit" in another forces a non-native reader to pause and confirm that they are the same thing. This small tax adds up across a long document and erodes confidence in the whole procedure. Choosing one term per concept and using it every time, even at the cost of some stylistic repetition that a native-English editor might otherwise flag, removes this friction entirely.

Photographs and simple diagrams do work that text alone cannot, particularly for steps involving visual judgement, such as identifying the colour change that signals a titration endpoint, distinguishing between a healthy and a stressed larva, or the correct orientation of a piece of equipment during assembly. A single labelled photograph placed next to the relevant step often communicates more reliably across all literacy and language levels in a mixed workforce than an additional paragraph of description. Testing a draft procedure with actual floor staff before finalising it, ideally staff at a range of experience levels rather than only the most senior technician, surfaces these gaps quickly: a step that seemed self-evident to the author is often the one a newer or non-native-speaking staff member stumbles on first.

Involving Farm Floor Staff in SOP Drafting

Procedures drafted entirely by management or technical staff, without input from those who perform the task daily, routinely miss practical details that only become obvious on the floor: the order operators actually prefer, the tool substitutions that work in practice, and the step that looks unnecessary on paper but prevents a recurring problem that only the person doing the task every day has seen happen.

This is not merely a courtesy extended to floor staff; it is a source of information that management and technical authors often lack. A supervisor drafting a broodstock handling procedure from a textbook or a previous employer's documentation will describe the theoretically correct sequence. A technician who has handled that species of broodstock daily for two years knows which step in that sequence causes the fish to thrash, which grip actually holds a wet, stressed fish still, and which supposedly optional step prevents an injury that reliably occurs without it. None of this is likely to appear in a document drafted without their input, however technically sound it may be in other respects.

Involving farm floor staff in drafting or reviewing a procedure before it is finalised improves both its accuracy and the likelihood that staff will follow it, since a document they helped shape carries more ownership than one handed down from above. In practice, this involvement need not be elaborate: a short review session in which a draft procedure is read through step by step with two or three of the staff who will use it, with the explicit instruction to flag anything that does not match how the task is actually done, catches most of the practical gaps that a purely desk-based draft would carry forward into the final document. The additional time this takes at the drafting stage is consistently smaller than the time lost later to a procedure that staff quietly work around rather than follow.

Building a Review Cycle That Keeps Documents Current

An SOP that is accurate on the day it is written and never revisited becomes a liability as equipment, staff, and processes change. Many certification failures trace back not to poor practice on the floor, but to documentation that no longer matches what is actually being done: a procedure that still references a discontinued chemical treatment. This stocking density was revised eighteen months ago on the floor but never in the document. A step refers to equipment that has since been replaced.

A workable review cycle assigns clear ownership for each procedure, so that a specific person, not a department, is accountable for keeping it current. It sets a fixed review interval appropriate to how quickly the underlying process for that procedure changes; a broodstock handling protocol may remain stable for years, while a water treatment procedure tied to seasonally variable source water may require a shorter cycle. It also treats any deviation discovered during an internal audit or any near miss reported by staff as a trigger for immediate document review, rather than waiting for the next scheduled cycle, because a known gap between the document and practice is exactly the condition that leads to certification failures and preventable losses.

The ownership element deserves particular attention, because a review cycle without a named owner tends to lapse quietly. When responsibility is diffuse, split across a department or an entire management team, a review that falls due tends to be deferred by everyone, on the reasonable but collectively costly assumption that someone else will get to it. Naming a single accountable owner for each procedure, even when several people contribute to the review, closes this gap. Pairing that ownership with a simple, visible tracker, such as a shared log listing every procedure, its owner, its review interval, and the date of its last review, makes it easy for a facility manager to see at a glance which documents are current and which are overdue, without needing to open each individual procedure to check.

Common Reasons SOPs Get Abandoned

Excessive length is one of the most common reasons a procedure is ignored: staff under time pressure will not read three pages to complete a five-minute task, and

a document that requires them to do so trains them, quite reasonably, to stop consulting it altogether. Length creeps in gradually rather than by design. Each revision adds a clarifying sentence, a caveat for an edge case that happened once, or a paragraph explaining the reasoning behind a step. Individually reasonable, these additions add up to a document that has grown well past the point where a staff member under time pressure will read it in full.

Jargon that does not match the audience is another common failure, particularly when a procedure is translated or adapted from another facility without adjusting to local terminology. A procedure written by a technical specialist for other technical specialists, then handed to floor staff without revision, carries assumptions about vocabulary and prior knowledge that the intended reader does not share. This is distinct from the literacy and language issue discussed earlier; it can affect native English speakers just as easily when the jargon is specific to a discipline, a piece of equipment, or a previous facility's internal shorthand that never made sense outside that context.

A third common failure is a lack of staff involvement in drafting, which produces documents that are technically correct but practically unworkable. Staff quickly learn to work around them rather than through them. Once that pattern sets in at a facility, it tends to generalise: staff who have learned that one procedure does not match reality become sceptical of all procedures, including those that would otherwise have served them well, and the informal, undocumented version of every task becomes the de facto standard regardless of what is written down.

A fourth, less-discussed failure is a review cycle that exists on paper but is not actually followed, creating the illusion of currency without its substance. A procedure with a recent-looking review date, yet whose content has not meaningfully changed in years despite known process changes on the floor, is arguably worse than one that is honestly out of date, because staff and auditors alike may trust a date they should not.

A Practical Template Approach

A workable template divides the document into a short purpose statement, a numbered sequence of steps with critical safety or quality checkpoints clearly flagged, and a brief troubleshooting section covering the two or three most common deviations staff encounter. The purpose statement answers, in one or two sentences, what the procedure is for and when it applies, so a reader can confirm within seconds that they have the right document. The numbered steps carry the working content of the procedure, written as single actions in the order they are performed, with checkpoints such as a required verification, a hold point, or a safety confirmation clearly distinguished from the surrounding routine steps. The troubleshooting section, often the most-used part of the document in practice, addresses the handful of deviations staff encounter: what to do if a reading is out of range, if a piece of equipment behaves unexpectedly, or if a step cannot be completed as written because of a site-specific constraint.



This structure is deliberately shorter and more visual than a typical audit-oriented SOP. Where full regulatory detail is required for certification, such as the underlying scientific rationale for a parameter, a full citation of the relevant standard, or an exhaustive list of edge cases, it can be placed in a linked reference document or an appendix rather than in the working procedure staff use daily. This keeps the floor-level document usable without sacrificing compliance: the auditor can still find everything needed to verify control, and the technician at the tank is not required to read beyond it to find step six.

A useful discipline when drafting or revising a procedure under this template is to ask, of every sentence added, whether it changes what the reader does next. A sentence that explains why a step exists, without changing the action itself, usually belongs in the linked reference material rather than in the working steps. A sentence that changes the action, the sequence, or the checkpoint belongs in the numbered steps. Applying this test consistently is what keeps a template-based procedure from gradually regrowing to the same unusable length it was designed to avoid.

Conclusion

The gap between what is written down and what actually happens on the farm floor is rarely a training problem. It is usually a documentation design problem, and it is fixable with the same rigour applied to any other production process: observe how the work is actually done, design the document around that reality rather than an idealised version, and build in a mechanism to keep the document honest as conditions change.

SOPs that staff actually use share a common set of traits: they are short; they are built around real workflows; they are shaped by input from the people who perform the task; they are written for the literacy and language levels of the people who will read them; and they are kept current through a review cycle with clear ownership. None of this requires new technology, only a different starting assumption about who the document is really for, and the discipline to test that assumption against the floor rather than against an auditor's checklist alone.

Aquaculture



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More Than Giving Fish a Pink Complexion: Astaxanthin supporting key metabolic roles above and beyond pigmentation in aquaculture

Modern aquaculture needs health oriented solutions that work under commercial farming conditions to ensure quality and viable safer products for the consumer. As production becomes more intensive, farmed fish will be exposed to stress, higher pathogen interactions, and a greater risk of poor performance. This has generated increased interest in feed additives that support fish health while also fitting industry goals for sustainability and reduced antibiotic use.

Astaxanthin (AX) is best known as the carotenoid that gives certain fish such as salmonids and some crustaceans their characteristic pink-reddish colour, but its role in aquafeeds is much broader and deeper than just aesthetic attributes (Lim et al., 2018). Research indicates that this molecule functions as a nutrient supporting antioxidant defence, reducing inflammation, boosting stress resilience, and enhancing disease resistance (Meng et al., 2024). In practical terms, it is increasingly viewed as a health-supporting ingredient or dietary feed additive rather than simply a pigment source in aquaculture. It is well understood that fish cannot synthesise carotenoids on their own (*de novo*), so they must obtain astaxanthin from the diet (Davies, 2018). That makes feed formulation the key route for delivering both pigmentation and health benefits under typical farmed conditions. Across the published studies reviewed, the strongest responses are generally linked to improved antioxidant capacity, better immune balance, and more stable performance under intensive rearing and environmentally related stress conditions.

How astaxanthin works metabolically

The main value of astaxanthin comes from its ability to reduce oxidative stress and help regulate immune

responses. At the cellular level, it supports antioxidant systems that protect tissues from damage caused by reactive oxygen species (ROS). At the same time, it can suppress excessive inflammatory signalling, which helps fish avoid the costs of chronic immune activation. This synergistic combination matters commercially (Song et al., 2017; Meng et al., 2024). This article highlights two central mechanisms. First, astaxanthin activates the Nrf2-ARE pathway, which increases the expression of protective antioxidant enzymes such as superoxide dismutase, catalase, glutathione peroxidase, and related defence systems (Davinelli et al., 2022). Secondly, it reduces over-activation of NF-kB-linked inflammatory pathways, lowering expression of key pro-inflammatory signals such as TNF-alpha and interleukins in several fish models evaluated This combination matters commercially under different aquaculture scenarios with significance to stress induced inflammation. Figure 1 shows schematically these interdependent systems and gene expression pathways operating in fish such salmonid species.

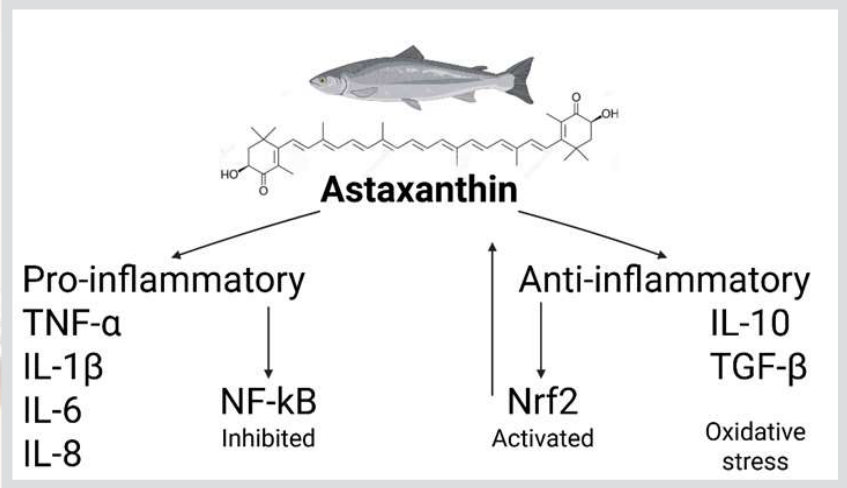


Figure 1. Astaxanthin and its involvement in the downregulation and upregulation of pro-inflammatory and anti-inflammatory controlling genes in a salmonid fish model *(© SJD)*

Fish in intensive production systems such as Atlantic salmon are regularly challenged by handling, temperature shifts, variable oxygen, metabolic stress, and infectious agents. A nutrient that improves antioxidant status while moderating inflammation can help maintain tissue integrity, support immune readiness, and reduce the performance losses and even mortality that often follow acute and chronic stress events. From this standpoint, Trine et al. (2021) highlighted the functional transcriptomics influences of AX in Atlantic salmon (Salmo salar) fed low fishmeal level diets placing potential nutritional margins under intensive production. Although the exact response varies by species and production context, the direction of effect is broadly consistent: astaxanthin tends to support health, improve antioxidant status, and enhance defence responses when used at appropriate inclusion levels as in the scheme depicted in Figure 2.

The evidence points to important roles in tissue protection, metabolism, pigmentation, and control of inflammatory induced stress. It has been reported that low or absent astaxanthin can trigger signs of oxidative strain and inflammatory responses, especially in muscle and other metabolically active tissues (Chen et al., 2024). This suggests that astaxanthin contributes not only to final flesh colour but also to general physiological stability in fish and even in crustaceans like shrimp (Chien and Shiau, 2005; Mansour et al., 2022) Rainbow trout provides some of the clearest evidence for immune and antioxidant benefits due to substantial experimental studies performed on this species alone. These generally show improved expression of antioxidant and anti-inflammatory markers, support for intestinal health, and stronger blood and immune indicators when astaxanthin is included at moderate levels.

It was Shabanzadeh et al. (2023) who reported how dietary astaxanthin supplementation (~40-100mg Kg^{-1}) could elevate growth performance, immune status, antioxidant competence of rainbow trout (*Oncorhynchus mykiss*) and mitigate against Yersinia ruckeri infection in a controlled challenge scenario. Further investigations by Yang et al., (2024) also confirmed better resistance to pathogen insult, especially when more bioavailable delivery systems are used such as using nanoliposome-coated astaxanthin.

These workers observed that in largemouth bass (*Micropterus salmoides*), astaxanthin appears particularly relevant for the mitigation of metabolic and liver stress. The article also describes benefits linked to reduced oxidative damage, improved glucose handling, and protection against stress-related tissue injury. For example, in coral trout (*Plectropomus leopardus*) AX supplementation improved antioxidant activity, immune markers, and survival after bacterial challenge, which is especially relevant for high-value marine fish production as previously investigated by Xiaowen et al., (2022) For European seabass and seabream, there are also specific research investigations having demonstrated the importance of astaxanthin in fish health status. It has recently been shown that dietary astaxanthin (0, 20, 100, 500 mg kg^{-1} for 15–30 days) in gilthead seabream (Sparus aurata) promoted growth performance, modulated immune and antioxidant status, affected lipid metabolism, and supported general health status indices (Campos-Sánchez, & Esteban (2024). Their study reports improved pigmentation, immune and endocrine modulation, stress reduction and overall fish health with AX incorporation in aquaculture diet. In seabass (*Dicentrachus labrax*) we have evidence by Saleh et al. (2018) of reduced hepatic antioxidant enzyme activities (SOD, GPx) with increasing AX, suggesting lower oxidative stress. A gradual increase in intestinal mucosal phagocytic and lysozyme activities, indicating an immunostimulant effect has been

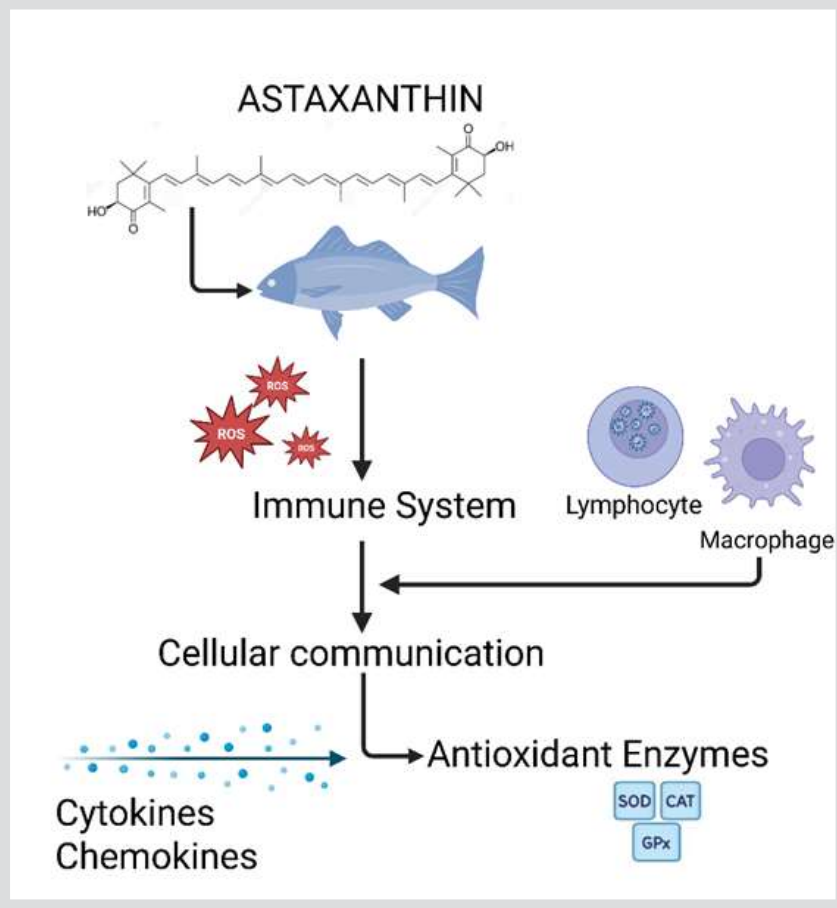


Figure 2. The general role of astaxanthin in the mitigation of reactive oxygen species in cellular-based defence systems of fish (macrophage, lymphocyte and antioxidant enzymes) through associated cellular communication pathways. ***Created by Wan, A. (2026)***

observed with incremental AX addition in experimental diets. Additionally, improved tolerance to acute osmotic stress (salinity drop from 37 to 0.3‰), with 36.9% higher survival than control at 100 mg kg $^{-1}$ has been recorded in such stress inducing challenges with seabass.

Inclusion level and formulation

One of the most useful commercial messages from this article is that astaxanthin does not behave as a simple "more is better" additive in aquatic animal nutrition. Responses are dose dependent, and the most reliable benefits are usually seen at moderate diet inclusion levels. Across species, this report identifies around 30 to 100 mg/kg diet as the most practical range for balancing efficacy, safety, and cost, although some species may respond at lower or slightly higher levels. Lower inclusion levels can still support antioxidant defence and gut function, particularly in sensitive species or when bioavailability is improved. Moderate levels tend to produce the best overall combination of health, immune, and stress-resilience benefits. In contrast, excessive levels can diminish benefits and may cause antagonistic pro-oxidant or pro-inflammatory effects, highlighting the importance of careful formulation. It should be noted that form matters as much as dose (dietary inclusion rate). The article notes that natural astaxanthin sources, especially from algae such as *Haematococcus pluvialis* and other biological systems like yeasts (e.g. *Phaffia rhodozyma* and bacteria (e.g. *Paracoccus carotinifaciens.*), can offer advantages in bioavailability and broader biological activity (Elbahnaswy and Elshopakey (2024). New delivery approaches such as nano-encapsulation and lipid-based systems may also improve absorption, protect the compound during processing such as in extrusion, and allow lower use rates for similar biological responses.

Commercial relevance

From a technical commercial perspective, astaxanthin has value in four linked areas: health management, stress mitigation, growth support, and final product quality. Healthier fish are less likely to lose performance during routine production challenges, and stronger natural defences can reduce exposure to disease-related losses. This is important in a sector under pressure to lower antibiotic dependence and improve welfare outcomes. There are also quality and market advantages. In salmonids, astaxanthin remains essential for flesh colour, but this article indicates that its antioxidant effects are crucial to preserve tissue quality and reduce oxidative deterioration. That means the ingredient can contribute to both farm performance and product value, improving the business case when benefits are assessed across the full production cycle. Cost still remains a major consideration for the choice of source. Synthetic astaxanthin still dominates commercial aquafeeds because it is more affordable, while natural sources are usually more expensive, they offer significant advantages. Even so, this article suggests that improved production systems, alternative biological sources, and circular-economy derived raw materials could narrow that gap over time, especially where buyers place a premium on natural or sustainability-led production claims. Overall, we must position astaxanthin in its various forms as a strategic functional ingredient for modern aquaculture applications. For feed companies and producers, the key opportunity is to use the right source, delivery system, and inclusion level to capture both its optimal biological and economic value.

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Aquaculture



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What Role Can the Aquaculture Centre of Excellence at Stellenbosch University Play in Aquaculture Training, Research & Development in Africa?

1. Introduction

Aquaculture is one of the fastest-growing food production sectors globally and is increasingly recognized as a key contributor to food security, employment creation, and economic development. In Africa, however, aquaculture production remains relatively underdeveloped compared to other regions, with only a few of the 54 countries realising the potential. Population growth, climate change, and declining capture fisheries make the expansion of aquaculture critical for sustainable food systems.

The **Aquaculture Centre of Excellence at Stellenbosch University** has emerged as an important hub for research, training, and innovation aimed at strengthening the aquaculture sector across Africa. Through interdisciplinary research, capacity building, and industry partnerships, the centre is positioned to contribute significantly to the sustainable development of aquaculture on the continent.

2. Overview of the Aquaculture Centre of Excellence

The Aquaculture Centre of Excellence (CoE) at Stellenbosch University (SU) is a **collaborative research hub** bringing together national and international experts working on aquaculture production systems and aquatic ecology.

The CoE builds on decades of aquaculture research

conducted at SU , where the Aquaculture Portfolio was established in **1989** to support the development of aquaculture in Southern Africa through high-quality education, research, and technical services.

Key characteristics of the CoE include:

- Interdisciplinary collaboration across departments such as Animal Sciences, Microbiology, Genetics, Food Science, Process Engineering, Conservation and Biodiversity and Agricultural Economics.
- Training programmes at undergraduate, postgraduate, and SU accredited professional short courses.
- Research facilities including experimental farms and laboratories.
- Partnerships with industry, government, and international research institutions.

These capabilities and networks position the CoE as a strategic platform for advancing aquaculture innovation and capacity development in Africa.

3. Contribution to Human Capacity Development

One of the greatest constraints to aquaculture development in Africa is the **shortage of skilled professionals and technical expertise**. Many times, Aquaculture students in Africa lack practical knowhow and hands-on experience.

The CoE can address this challenge through:

3.1 Education and Training

Stellenbosch University is a highly regarded tertiary institution (# 296 in the world and 3rd in Africa – QS World University Rankings, 2026). The Aquaculture academic offering includes programmes ranging from Bachelor to Doctorate levels, as well as accredited short courses and distance-learning programmes designed for professionals in the sector.

These programmes focus on core Aquaculture areas such as:

- Fish nutrition and feed formulation.
- Aquatic animal health and disease management.
- Water quality and environmental monitoring.
- Aquaculture systems engineering.
- Aquaculture economics and value chains.

By training scientists, extension officers, and aquaculture entrepreneurs, the CoE contributes towards building skilled workforces needed to expand aquaculture across the continent.

3.2 Regional Training and Knowledge Transfer

Training initiatives have also been extended beyond South Africa through workshops and capacity-building programmes conducted in many African countries, including, Ghana, Malawi, Egypt, Zambia, Uganda, Mauritius, Seychelles, Angola, Mozambique, Namibia, and Lesotho, strengthening regional expertise in





aquaculture production and management.

4. Research and Innovation for Sustainable Aquaculture

Research and technological innovation are essential for improving productivity and sustainability in African aquaculture systems.

The CoE contributes to this through applied and interdisciplinary research, including:

4.1 Aquaculture Production Systems

Research focuses on improving aquaculture production technologies, including:

- Recirculating aquaculture systems (RAS).
- Aquaponics and integrated farming systems.
- Sustainable feed and nutrition strategies.
- Breeding and genetics of farmed fish species.

Aquaponics is an example where fish and plants production have been integrated in a closed-loop system in both fresh- and seawater, improving water efficiency and sustainability—particularly relevant in water-scarce regions of Africa.

4.2 Environmental Sustainability

The CoE also investigates environmental impacts of aquaculture, including water quality management and ecosystem impacts, ensuring that aquaculture expansion aligns with sustainable water use and protecting biodiversity.

5. Supporting Industry Development and Innovation

The CoE also plays a key role in **linking academia with industry.**

Through partnerships with aquaculture farms, feed manufacturers, and technology developers, the centre can:

- Test and commercialise new aquaculture technologies.
- Provide technical advisory services.
- Support the development of new aquaculture enterprises.
- Facilitate technology transfer to small- and medium scale farmers.

These collaborations help bridge the gap between research and commercial aquaculture operations, increasing the success rate of emerging enterprises through informed decision making and understanding realistic performance.

6. Regional Collaboration and Policy Support

The CoE is also part of a broader **African Union Network of Centre of Excellences** coordinated through continental initiatives. This network includes institutions in countries such as Egypt, Ghana, Uganda, Malawi, and Namibia.

Through this network, the CoE contributes to:

- Collaborative research projects across Africa.
- Policy development for sustainable aquaculture.

• Harmonisation of training programmes.
• Knowledge sharing among African universities and research institutions.
• Combined resource mobilisation.

These collaborations strengthen regional integration and promote coordinated development of the aquaculture sector through establishing financial stability and capacity building.

7. Contribution to Food Security and Economic Development

Aquaculture development is increasingly recognised as a solution to several socio-economic challenges facing Africa.

By supporting aquaculture expansion, the CoE contributes to:

• **Improved food and nutrition security** through increased fish production.
• **Job creation,** particularly in rural and coastal communities.
• **Economic diversification** within agricultural sectors.
• **Climate-resilient food production systems.**
• **Succession in leadership and governance.**

Governments across Africa have identified aquaculture as a priority sector due to its potential to enhance food supply, generate employment, and stimulate economic growth.

8. Challenges and Opportunities

Despite its potential impact, the CoE have to address several challenges confronting Aquaculture in Africa:

• Limited funding for research and infrastructure.
• Incoherent education and training programmes.
• Insufficient policy support in some African countries.
• Limited access to appropriate technology among small-and medium scale farmers.
• Weak aquaculture value chains in many regions.

However, these challenges also present opportunities for the CoE to expand its role through innovation, partnerships, and capacity development.

9. Conclusion

The Aquaculture Centre of Excellence at Stellenbosch University has the potential to play a transformative role in aquaculture development across Africa. Through education, research, innovation, and regional collaboration, the CoE can contribute to building a skilled workforce, advancing sustainable aquaculture technologies, and strengthening the aquaculture value chain.

As Africa seeks solutions to food insecurity, unemployment, and environmental challenges, institutions such as the Stellenbosch University Aquaculture Centre of Excellence will be critical in driving sustainable growth in the aquaculture sector and supporting the continent's long-term development goals.





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Why Are All-Female Populations Preferred in Rainbow Trout Farming?

A Simple Question with a More Complex Answer

The use of all-female populations in rainbow trout (Oncorhynchus mykiss) farming has been a well-established production strategy for many years. This approach can become particularly important from a commercial perspective when fish are grown to larger market sizes. However, the commonly used statement that "**females grow better than males**" should be treated with some caution. The available scientific literature does not support a universal biological rule that female rainbow trout always grow faster than males at all ages, across all genetic lines, or under all farming conditions. Instead, the relationship between sex and growth may vary with age, genetic background, farming conditions and, importantly, the stage of sexual maturation. Therefore, to understand the commercial rationale for all-female production, it may be more useful to ask not simply "**Which sex grows faster?**", but rather "**How do growth and sexual maturation interact over time?**"

Can Males Grow Better Than Females at Certain Stages?

Yes. There are clear examples of this in the literature. Crandell and Gall (1993) followed individually tagged rainbow trout up to 740 days after fertilization to examine the relationships among sex, body weight, and sexual maturation. The fish were grouped as females, males that matured early at one year of age, and males that matured later. Between days 159 and 335, body weights did not differ significantly between females and later-maturing males. However, from days 362 to 628, these males were significantly heavier than the females. Even more notably, males that later matured at one year of age were already heavier than other males before any visible signs of sexual development appeared. The authors interpreted this finding as evidence of a strong relationship between body size and early maturation. They also reported that, after maturation, the negative effect on growth became more evident in early-maturing males. A similar pattern was reported by Allen et al. (2017) in a commercial rainbow trout strain. Males that matured at two years of age were significantly heavier than immature males and females at both 381 and 614 days, and they also showed higher specific growth rates. The authors further reported that higher body weight was an important indicator of the likelihood of early male maturation. These findings

highlight an important point: being male does not automatically mean having poorer growth performance. At certain stages, fast-growing males may actually be heavier than females.

The biological paradox is that rapid growth may also be associated with a greater probability of reaching sexual maturity earlier. Allen et al. (2017) likewise emphasized that fast-growing and heavier males showed a greater tendency toward early maturation, although the strength of this relationship varied among genetic lines and families.

Why, Then, Do Some Studies Report Better Growth in All-Female Stocks?

On the other hand, several studies have also reported positive production performance in all-female stocks. Sheehan et al. (1999), in a 265-day production trial, found that all-female diploid and triploid rainbow trout groups showed better growth than a mixed-sex diploid group. This study is therefore one of the key pieces of evidence supporting the commercial value of all-female stocks. However, this result should not be generalized to mean that "females are biologically faster-growing than males." Comparing all-female and mixed-sex populations is not the same as directly comparing the growth of individual females and males. Several factors may influence the outcome simultaneously, including population sex structure, the timing of male maturation, production duration, and diploid or triploid status. For this reason, the findings of Sheehan et al. (1999) should not be seen as contradicting those of Crandell and Gall (1993) or Allen et al. (2017). Rather, these studies describe different parts of the same dynamic relationship between growth and sexual maturation under different experimental and production conditions.

The Key Issue Is Not Simply Growth, but the Timing of Maturation

This is where the main commercial rationale for all-female production becomes clear. Male rainbow trout generally tend to reach sexual maturity earlier than females. Early sexual maturation can create undesirable consequences in aquaculture, especially when it occurs before the fish reach the intended market size. Sexual maturation is metabolically demanding. An increasing share of the fish's energy and nutrients is directed not only toward somatic growth, but also toward gonadal development and reproduction. Crandell and Gall (1993) emphasized that sexual maturation before market size may be associated with reduced growth and poorer flesh quality. Bye and Lincoln (1986) also discussed in detail the importance of controlling sexual maturation in commercial rainbow trout production. A fast-growing male may therefore be heavier than a female during the early stages of production. However, if the production cycle continues and that male enters early maturation, the biological and commercial situation may change. For this reason, the advantage of all-female production should not simply be described as "females grow better." All-female production is not based on the assumption that males are intrinsically slower-growing. Rather, its main value lies in reducing the production effects associated with earlier sexual maturation in males.

The Advantage Depends on the Production Cycle

This distinction also helps explain why all-female stocks may not provide the same level of benefit in every farming system. If fish are harvested at a small or medium portion size before males reach their first sexual maturation, the growth advantage of using all-female stocks may be limited. During this period, some males may even show better growth performance than females. In contrast, as the production cycle becomes longer and fish are grown to large portion size, fillet size, or higher market weights, early male maturation may become increasingly important. Under these conditions, the biological and management advantages of all-female stocks may become more evident. The expected benefit of all-female production should therefore be evaluated together with factors such as age, genetic line, water



Figure 1. Mature female rainbow trout (original photograph). All-female production is based on crossing genetically XX neomale broodstock with normal XX females.



How Are All-Female Rainbow Trout Produced?

Genetics and broodstock management for producing genetically XX female offspring

Key stages of production

1 Known XX female stock

Production starts with genetically female trout.

- Females: XX
- Males: XY, usually carrying *sdY*

2 Masculinisation

- Selected XX juveniles can be masculinised during gonadal differentiation.
- Chromosomal sex does not change.

3 XX neomales

- These fish remain genetically XX.
- They develop testes and produce sperm.

4 Genetic verification

- Markers such as *sdY* or *OmyY1* can help distinguish true XY males from XX neomales.

5 Crossing

XX NEOMALE × XX FEMALE

- XX neomale × XX female
- Sperm carries X
- Eggs carry X

6 Result

X + X = XX

- X + X = XX
- This cross produces genetically XX offspring.

7 Commercial stock

- The XX offspring are used in grow-out.
- They support a more uniform and predictable stock.

Why are all-female stocks used?

- Growth advantage is not inherently female-specific
- Males often mature earlier
- Early maturation diverts energy from growth to gonad development
- This may affect growth, flesh quality and stock uniformity
- Benefits are most evident at larger market sizes

Important note

Market fish are not hormone-treated

- Hormone use is limited to the broodstock step
- Fish for human consumption are not directly treated

Scientific nuance

- Genetically XX does not always mean phenotypically female
- In XX × XX crosses, XY offspring are not expected
- Rare spontaneous masculinisation or intersex phenotypes may still occur
- This reflects biological variation, not failure of the genetic principle

Conclusion

All-female rainbow trout production combines genetics, reproductive biology and broodstock management to support more uniform and predictable production, especially at larger market sizes.

Key references

Johnstone *et al.*, 1978; Bye & Lincoln, 1986; Crandell & Gall, 1993; Piferrer, 2001; Sheehan *et al.*, 1999; Yano *et al.*, 2012; Allen *et al.*, 2017; Fraslin *et al.*, 2020; Weber *et al.*, 2020; Weber & Leeds, 2022; Colihueque & Parraguez, 2024.

Figure 2. How all-female rainbow trout are produced?

temperature, feeding, photoperiod, farming system, production duration, and target market size. Allen et al. (2017) also showed that the relationship between growth and early maturation may vary among genetic lines and even among families within the same line.

Stock Uniformity and Product Quality

The advantages of all-female stocks should not be reduced to average growth rate alone. In a mixed-sex population, not all males reach sexual maturity at the same time. Some individuals mature early, while others continue somatic growth. As the production cycle progresses, this can increase variation within the stock in terms of physiological condition, body composition, external appearance, and market characteristics. Reducing this variability may be particularly important for commercial farms that require consistent product size and quality. The classic review by Bye and Lincoln (1986) also considered the control of sexual maturation not only from the perspective of growth, but also in relation to product quality and production management. In this sense, all-female farming can be viewed not only as a growth strategy, but also as a stock management approach designed to improve production uniformity and make harvest outcomes more predictable.

How Are All-Female Rainbow Trout Produced?

Sex determination in rainbow trout is largely based on an XX/XY system with male heterogamety. Genetic females are XX, whereas genetic males are typically XY. The **sdY** gene has been identified as the major male sex-determining gene in rainbow trout (Yano et al., 2012).

All-female production takes advantage of the fact that genetic sex and phenotypic sex can be separated. Genetically XX individuals can be directed toward a male phenotype through controlled androgen treatment during the sensitive period of gonadal differentiation.

This treatment does not alter the chromosome complement. The fish remains genetically XX but can develop functional testes and produce sperm. These individuals are commonly referred to as **XX neomales, masculinised females**, or **sex-reversed females**. The use of genetically female salmonids that have been phenotypically masculinised to produce all-female offspring has been known for many years (Johnstone et al., 1978; Bye & Lincoln, 1986; Piferrer, 2001).

Traditionally, androgens have been administered through the diet, while more recent studies have examined controlled immersion protocols. Weber et al. (2020) showed that immersion in 17α-methyltestosterone during early development can induce masculinisation in XX rainbow trout. Weber and Leeds (2022) further demonstrated that both the timing and duration of treatment are important for producing functional neomales. It should also be kept in mind that these procedures are part of broodstock production technology, and their use must be considered within the regulatory framework of the country in which they are applied.

Neomale Sperm Quality and Fertilization Success

Producing an XX neomale is only the first step. For successful broodstock use, the fish must produce functional sperm capable of fertilizing eggs. Geffen and Evans (2000) demonstrated the fertilization capacity of sperm from sex-reversed female rainbow trout. Ciereszko et al. (2015) showed that testicular spermatozoa collected from XX neomales can be matured in vitro using artificial seminal plasma or suitable extenders. Judycka et al. (2021) also provided a comprehensive review of the characteristics and cryopreservation of semen from sex-reversed female salmonids.

Together, these studies show that all-female production involves more than sex reversal alone. It also requires appropriate sperm quality assessment and broodstock management.

XX Neomale × XX Female: The Genetic Logic

A normal XX female produces eggs that carry only the X chromosome. Because an XX neomale also remains chromosomally XX, its sperm also carries only the X chromosome.

Therefore: **XX neomale × XX female → XX offspring**

In this cross, XY offspring carrying a Y chromosome are not expected. The masculinisation process does not create a new Y chromosome. For this reason, new neomale broodstock can again be produced from an all-female stock of known genetic origin generated through an XX × XX breeding system, allowing the same principle to be maintained across subsequent generations. When required, molecular sex-determination techniques can provide an additional level of quality assurance in broodstock management. Colihueque and Parraguez (2024) showed that Y-linked markers such as **sdY** and **OmyY1** can be used to distinguish true XY males from XX neomales. This approach may be especially useful when the genetic origin of the broodstock is uncertain or when additional quality control is required in commercial breeding programs.

Are Fish Produced for Human Consumption Treated with Hormones?

There is an important distinction here from both the producer and consumer perspectives. The offspring produced for commercial grow-out do not need to be treated with hormones. Androgen treatment is used at the broodstock production stage to produce the XX neomales required for all-female production. Eggs from normal XX females are fertilized with sperm from these neomales, and the resulting XX offspring are then transferred to commercial grow-out systems.

Therefore, the production generation raised for human consumption is not the direct target of the hormonal treatment used to produce neomales. Recent sex-reversal studies also consider androgen treatment primarily as a method for producing XX neomale broodstock for all-female offspring production, rather than as a treatment applied directly to commercial grow-out fish (Weber et al., 2020; Weber & Leeds, 2022).

Does "XX" Always Mean Phenotypically Female?

There is another important biological point to consider. Although offspring from an XX neomale × XX female cross are expected to be chromosomally XX, being genetically XX does not guarantee that every individual will necessarily develop as a phenotypic female. Fraslin et al. (2020) showed that spontaneous masculinisation and intersex phenotypes can occur at low frequencies in commercial XX rainbow trout populations. These individuals are not XY males. Although genetically XX, their gonadal development may follow a male or intermediate phenotype. This does not mean that the XX × XX production principle has failed or that a Y chromosome has somehow reappeared. Rather, it reflects the fact that the relationship between genotype and phenotype can occasionally vary. Therefore, when using the term "all-female," it is useful to distinguish between the genetic objective of producing XX offspring and the rare variations that may occur during phenotypic sex development.

What Is the Take-Home Message for Producers?

When the available scientific literature is considered as a whole, three main conclusions emerge.

First, it cannot be assumed that female rainbow trout always grow faster than males under all conditions. At certain stages of production, males may be heavier and may grow faster than females. Crandell and Gall (1993) and Allen et al. (2017) provide clear examples of this.

Second, growth and early sexual maturation are not independent processes. There is considerable evidence that faster-growing males may also have a greater tendency to mature early.

Third, the commercial advantage of all-female stocks comes largely from managing this relationship. Although studies such as Sheehan et al. (1999) have reported better production performance in all-female stocks under certain conditions, these findings should not be interpreted as evidence of a universal growth advantage of females. Instead, they should be considered together with population structure and maturation dynamics.

All-female production can therefore be better understood not simply as a strategy of "**selecting the faster-growing sex,**" but as a management approach designed to reduce the production consequences of early male maturation.

Conclusion

All-female rainbow trout production is therefore more complex than the simple statement that "**females grow better than males.**" It represents the practical application of the dynamic relationship between growth and sexual maturation, together with reproductive biology, genetics, broodstock management, and market objectives. When used under appropriate production conditions, all-female stocks can contribute to a more uniform, predictable, and manageable farming system.

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Japan's Yanmar Holdings Set to Acquire AKVA Group

Originally published by Minato News on LinkedIn: October 5, 2026

Yanmar Holdings, a Japanese industrial machinery and marine equipment group, announced on October 2 "recommended voluntary cash offer for AKVA Group," a major aquaculture technology company. The offer is recommended by AKVA Group's board.

According to AKVA Group, the company has entered into a transaction agreement with Pontos Bidco, a company indirectly owned by Yanmar Holdings, for a recommended voluntary cash offer by Pontos Bidco to acquire all issued and outstanding shares in AKVA Group.

The offer price is NOK 161 per share, representing a premium of approximately 67% to AKVA Group's dividend-adjusted volume-weighted average share price over the 60 trading days up to and including April 7. At this price, all issued and outstanding shares in AKVA Group are valued at approximately NOK 5.9 billion.

Yanmar Holdings is a privately held, family-owned group known in Japan for its small diesel engines and agricultural machinery.

Yanmar's CSR Report 2022 included land-based recirculating aquaculture as one of the company's directions in food production under YANMAR GREEN CHALLENGE 2050.

Yanmar Holdings has been involved in aquaculture in Japan for many years. It produces artificial oyster seed and launched a land-based sea urchin aquaculture project with Kita-Sanriku Factory in 2025, applying its fluid analysis and automated tank-cleaning technologies.

For Japanese eel, Yanmar Holdings jointly developed a new mass-production tank with the Japan Fisheries Research and Education Agency and Marino-Forum 21. The new tank successfully produced approximately 1,000 eel seedlings per tank. In 2025, it conducted a demonstration test of a remote automated feeding system for farmed yellowtail.

In 2025, Yanmar Holdings also formed a capital and business alliance with Aqua Stage, which has developed a closed recirculating land-based aquaculture system and farmed chum salmon, tiger pufferfish, Biwa trout, shrimp and flounder.

Minato News Japanese-language report (opening section available free):
https://www.minato-yamaguchi.co.jp/minato/e-minato/articles/165986
Yanmar Holdings news release:
https://www.yanmar.com/global/news/2026/10/02/170117.html

Japan's Yanmar Holdings Set to Acquire AKVA Group

Jan. 26, 2026 | Minato News

The Federal Agency for Fisheries of the Russian Federation decided on January 23 to increase the total allowable catch (TAC) for several species, including crabs, Atka mackerel, and cod for 2026. For Barents Sea king crab, the quota will be raised by 10% (1,210 metric tons) from the initial 2026 allocation, bringing the total to 13,900 tons.

The Barents Sea is the primary source of frozen king crab exports to Japan. The king crab TAC had been held steady at 12,690 tons for five consecutive years, from 2022 through the initial 2026 allocation announced last year. With this decision, the quota will be increased to 13,900 tons.

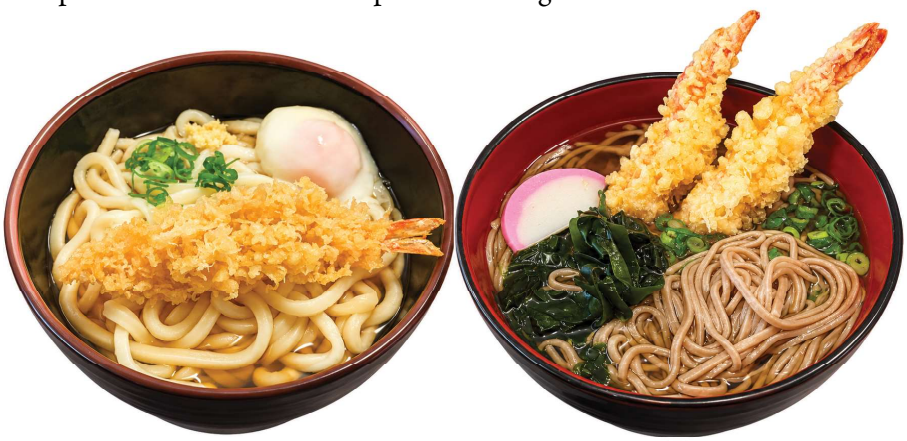
In Russia's Far East, quotas for several crab species will also be increased. The TAC for blue king crab, which is mainly shipped live to China, will rise by 7% (661 tons) to 9,638 tons, while the red king crab quota will increase by 0.3% (45 tons) to 13,247 tons. The quota for Tanner crab is also expected to rise by about 300 tons.

The quota increases are expected to be formally enacted once the Russian government revises the Ministry of Agriculture order setting the TAC for each species.

Minato News Releases Report on Japan's Shrimp Market Beyond the Trade Statistics

New report explores Japanese buyers' preferences, supplier differences and emerging product trends.

The report will remain available for purchase through at least the end of November 2026



Minato News, a Japanese seafood media outlet, released Inside Japan's Shrimp Market: Beyond the Trade Statistics on October 7, 2026. The 28-page English-language report examines Japan's shrimp market, including its structure, buyers' preferences and the roles of different products and suppliers.

Based on interviews with Japanese trading companies and wholesalers, the report explores market dynamics that are not fully reflected in official trade statistics. With the cooperation of Japanese trading company Nosui Corporation, it also provides estimates of product-form and species shares in Japan's 2025 frozen shrimp imports.

One focus is the different sales channels for Ecuadorian and Indian headless shell-on vannamei. According to the report, Ecuadorian products mainly supply Japanese retailers, while Indian products are primarily directed toward foodservice. Freezing methods, buyers' requirements and deveining techniques are among the factors examined.

The report also covers peeled shrimp, boiled and sushi shrimp, and Japanese-style breaded shrimp. Products that appear to have gained ground in Japan in 2025 include Indian peeled shrimp, Indian stretched shrimp used for tempura and other dishes, boiled and sushi shrimp from Southeast Asia, and Ecuadorian headless vannamei among shell-on products.

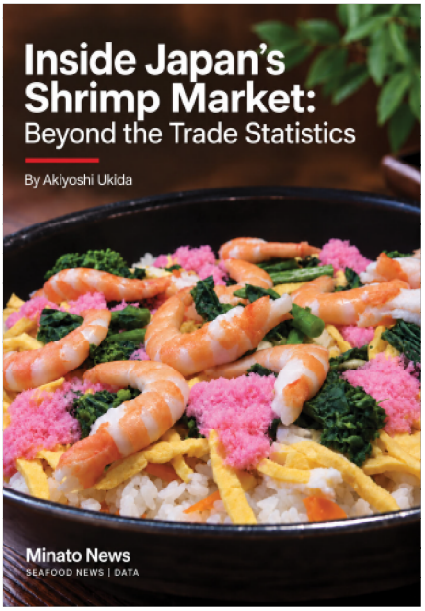
The author, Akiyoshi Ukida, Head of Minato News, has covered Japan's seafood industry since 1995. The report builds on insights from his presentation at the fifth Global Shrimp Forum, held in Utrecht, the Netherlands, on September 2, 2026, and includes additional topics not covered at the event.

For shrimp exporters, processors and seafood traders, the report offers insights into Japan's market structure and purchasing preferences that may help inform product development and market-entry strategies.

Report details: Inside Japan's Shrimp Market: Beyond the Trade Statistics | English-language PDF, 28 pages | US$29.

Further information and purchase:
https://minato-news.sellfy.store/p/inside-japans-shrimp-market-beyond-the-trade-statistics/

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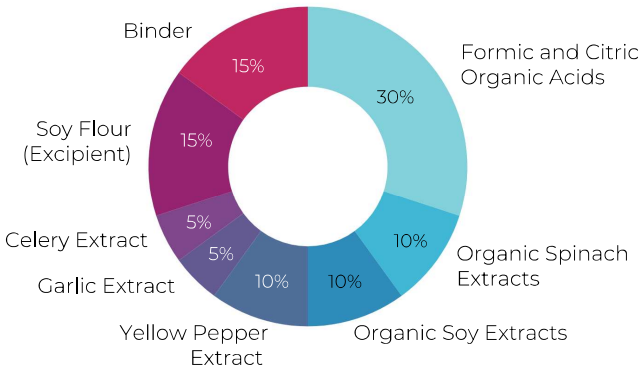
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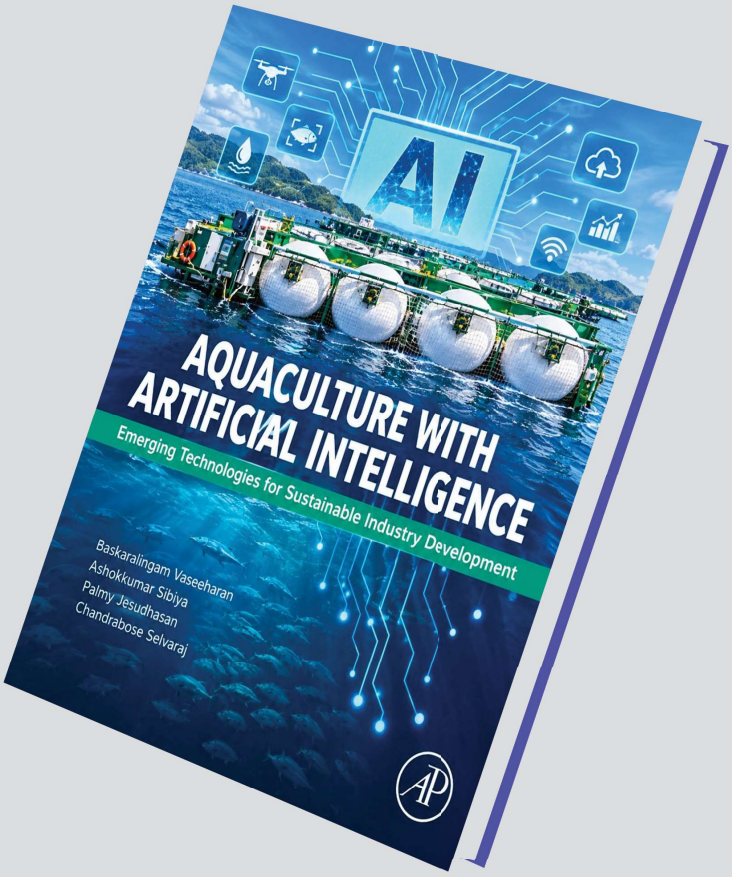
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Book introduction



Aquaculture with Artificial Intelligence
Emerging Technologies for Sustainable Industry Development

Author:
• Baskaralingam Vaseeharan, Ashokkumar Sibiya, Palmy Jesudhasan, Chandrabose Selvaraj

Publisher: • Elsevier
Edition: 1st Edition
Publication: August 2026
Language: English
400 pages
ISBN: 978-0-443-33704-8

About the Book

Aquaculture with Artificial Intelligence: Emerging Technologies for Sustainable Industry Development examines how artificial intelligence and emerging digital technologies are transforming aquaculture and contributing to more efficient, sustainable and data-driven production systems.

The book addresses major challenges facing modern aquaculture, including environmental management, disease prevention, resource optimization and the need for more precise decision-making. It explores how artificial intelligence, machine learning, computer vision, robotics, drones, Internet of Things (IoT), big data and cloud technologies can be integrated into aquaculture operations.

Among its key applications are automated feeding, water-quality monitoring, disease detection and protection, precision aquaculture and intelligent farm management. The book also examines emerging areas such as bioimaging, OMICS technologies, AI-assisted drug design, bioengineering and blockchain applications.

A notable feature of the book is its use of global case studies to demonstrate practical applications of AI in aquaculture rather than treating artificial intelligence solely as a theoretical technology. The final chapter considers future directions, research gaps and opportunities for further development.

Contents at a Glance

The book covers the transition from conventional aquaculture toward smart and digitalized production, followed by dedicated discussions of:

- Artificial intelligence and machine learning for aquaculture
- Bioimaging and AI-based disease monitoring
- AI-assisted feeding and drone technology
- IoT applications in aquaculture
- OMICS and computational technologies
- AI and aquatic animal health
- AI-assisted drug design
- Blockchain, cloud computing and big data
- Industrial applications of AI
- Future directions and research opportunities

About the Authors

The authors bring together expertise in aquaculture, aquatic animal health, biotechnology, immunology, genomics, bioinformatics and artificial intelligence. Lead author Baskaralingam Vaseeharan is Professor and Head of the Department of Animal Health and Management at Alagappa University, India. The other authors include researchers from Alagappa University, the USDA Agricultural Research Service and Saveetha Institute of Medical and Technical Sciences.

Why This Book Matters

The book reflects a significant shift in aquaculture from conventional production management toward precision, automation and data-driven decision-making. Its focus on AI applications across feeding, water quality, animal health and farm management makes it particularly relevant to researchers, technology developers, aquaculture professionals and industry leaders exploring the next generation of smart aquaculture.

Recommended for: Aquaculture researchers and professionals, farm managers, aquatic animal health specialists, data scientists, technology developers, environmental scientists and students working at the intersection of aquaculture and emerging technologies.

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