FUTURE AQUACULTURE

Vol. 1, Issue 1, October 2025

Future Aquaculture:
Innovate, Sustain, Nourish

FAO and the Sustainable Development Goals

Food and Agriculture Organization of the United Nations

FUTURE AQUACULTURE

Vol. 1, Issue 1, October 2025

ISSN: 3115-820X

CONTENT

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Future Aquaculture is published quarterly by Green Wave Publication (www.gwapub.com)

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Pioneering the New Wave of Aquaculture

Welcome to the inaugural issue of Future Aquaculture!

In today's world, where the challenges of feeding a growing population and preserving natural resources are becoming increasingly critical, aquaculture plays a vital and indispensable role. This industry not only provides a rich source of protein and nutrients but also helps reduce pressure on wild fisheries and marine environments through sustainable and innovative methods. Future Aquaculture was born with this vision and mission: to serve as a bridge between science and practice, and to build a brighter future for this industry.

Who are Our Readers?

At Future Aquaculture, we aim to cultivate a dynamic and informed community. Our readers include a wide range of professionals, enthusiasts, and students:

* Industry Experts and Professionals: From farm managers to veterinarians and engineers, this magazine is a platform for exchanging knowledge and staying updated on the latest innovations, equipment, and management techniques. We help you learn about the most current methods for cultivation, disease control, and increasing efficiency.

* Students and Researchers: If you are studying or conducting research in fields related to fisheries science, veterinary medicine, biotechnology, or environmental studies, Future Aquaculture will be a rich resource of scientific articles, research reports, and interviews with leading experts.

* Investors and Entrepreneurs: The aquaculture industry offers attractive investment opportunities with high growth potential. By analyzing market trends, introducing emerging technologies, and reviewing successful business models, we help you make more informed decisions.

* The General Public Interested in the Environment and Healthy Eating: Future Aquaculture is not just a specialized magazine. We present simple and engaging content to explain the role of aquaculture in global food security and the importance of consuming healthy seafood.

What is Our Goal?

Our main goal at Future Aquaculture is to become a trusted and inspiring reference for everyone in this field. We strive to achieve several key objectives by providing accurate, up-to-date, and practical content:

* Promoting Knowledge and New Technologies: Publishing scientific articles, news reports on new achievements, and introducing advanced equipment to improve farm performance.

* Creating a Link Between Industry and Academia: Providing a platform for scientific and industrial collaboration and bridging the gap between theoretical research and practical application.

* Raising Public Awareness: Informing the public about the importance of sustainable aquaculture and its role in environmental preservation and food security.

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

Editorial Director
Dr. Shahram Dadgar

The Pioneers of Sustainable Aquaculture: How We are Changing the Future of Global Food

Introduction

With the global population expected to approach 10 billion by 2050, sustainable food production is no longer optional—it is imperative. While aquaculture has emerged as a critical means of supplying high-quality protein, conventional practices have contributed to environmental degradation and unsustainable resource use. Fortunately, pioneering innovations and sustainable models are transforming aquaculture to support global food security while safeguarding ecosystems.

This article explores key advancements—Integrated Multi-Trophic Aquaculture (IMTA), alternative feeds, seaweed farming linked to carbon sequestration, robust certification systems, and the evolving carbon credit landscape—and reflects on how these innovations are reshaping global food systems.

1. Integrated Multi-Trophic Aquaculture (IMTA): Mimicking Nature's Balance

Integrated Multi-Trophic Aquaculture (IMTA) involves cultivating species from different trophic levels—such as fish, shellfish, and seaweed—in tandem so that the byproducts of one serve as inputs for another. This symbiotic approach enhances nutrient recovery, mitigates pollution, and improves ecosystem health.

A compelling example is a pilot project in the Bay of Fundy, Canada, co-culturing Atlantic salmon with blue mussels and kelp. Waste nutrients from the salmon fostered accelerated growth in mussels—reaching market size 8–10 months earlier—and boosted kelp growth by nearly 50%. Moreover, monitoring revealed that mussels grown near salmon did not accumulate contaminants and were indistinguishable from wild counterparts in taste and safety.

IMTA not only reduces environmental impact but also diversifies output—producing valuable crops and supporting the long-term viability of aquaculture systems.

2. Sustainable Feed: Single-Cell Proteins and Beyond

Traditional aquafeeds relying on wild-caught fish for fishmeal and oil contribute to ecosystem depletion. Enter Single-Cell Proteins (SCPs): microbial or algal-derived proteins offering a sustainable, high-quality alternative.

Companies such as Calysta use methanotrophic bacteria to convert methane into protein. This alternative, along with others derived from algae, fungi, and yeast, can reduce dependence on marine resources while improving gut health and immune responses in fish.

Transitioning to SCP-based and other plant-based feeds can significantly improve the sustainability and scalability of aquaculture nutrition.

3. Seaweed Farming: Blue Carbon, Environmental Services, and Potential Revenue

Carbon Sequestration

Seaweed farms offer vast climate benefits through carbon uptake. If even a modest percentage of global ocean surface were allocated to seaweed cultivation, the sequestration potential would be significant. Some species, such as giant kelp, can grow up to 50 cm per day and absorb considerable amounts of CO_2.

Environmental Credits and Ecosystem Services

The emerging aquaculture carbon credit market is expected to grow rapidly, driven by the integration of blue carbon initiatives. Seaweed and shellfish farming are among the most promising tools in this space, contributing to nutrient removal, biodiversity restoration, and ocean health.

However, challenges remain regarding the verification of carbon sequestration and the development of viable financial markets. Some pilot programs have begun issuing nutrient removal credits and exploring integration into carbon credit frameworks.

4. Certification Systems: Ensuring Responsibility and Consumer Trust

Certification systems play a crucial role in legitimizing sustainable aquaculture practices. The Aquaculture Stewardship Council (ASC), founded by the WWF and IDH, implements environmental and social standards for aquaculture across multiple species.

In partnership with the Marine Stewardship Council (MSC), ASC has introduced a joint Seaweed Standard, providing third-party audit processes and traceability mechanisms. This ensures that seaweed and other aquaculture products are responsibly farmed, both socially and environmentally.

In addition to ASC and MSC, other certifications such as Best Aquaculture Practices (BAP) and GlobalG.A.P. contribute to improving industry standards, offering transparency for consumers and rewarding responsible producers.

5. Technology & Policy Synergies

Aquaculture is increasingly driven by technological innovation. AI-powered sensors, drones, and real-time data analytics are being used to optimize feed efficiency, monitor fish health, and reduce antibiotic use. These advancements improve not only profitability but also environmental compliance.

Policy frameworks are evolving to support sustainable aquaculture. In the European Union, carbon border taxes on seafood imports are being introduced, and in California, carbon disclosure regulations are affecting seafood companies. Norway, meanwhile, offers a model for licensing, regulation, and monitoring that enables large-scale yet sustainable operations.

Such synergy between innovation and regulation is essential for aquaculture to meet climate and food security goals.

6. Social and Economic Impact

Sustainably managed aquaculture supports livelihoods, food security, and equitable growth. Community-based IMTA and seaweed projects in coastal areas have empowered smallholder farmers and women, especially in Southeast Asia and Africa.

Certification schemes ensure fair labor practices and community engagement, aligning with the UN Sustainable Development Goals (SDGs). As aquaculture grows, so too does its potential to contribute to inclusive and sustainable economic development.

Conclusion

The pioneers of sustainable aquaculture are boldly reshaping how humanity produces food. Through innovations such as IMTA, alternative microbial feeds, regenerative seaweed farming, rigorous certification, and smart policy integration, they›ve created a resilient, climate-conscious framework for feeding the planet.

These practices demonstrate that aquaculture can reconcile productivity with planetary health—ushering in an era where healthy oceans and healthy populations coexist. As we continue to refine technologies, strengthen standards, and foster multi-stakeholder collaboration, aquaculture stands as a cornerstone of sustainable global food systems.

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Arsenic in Seafood

Should consumers be concerned about the presence of arsenic in Seafood?

Initial considerations

Seafood, or aquafood in a broad sense – including freshwater, brackish, and marine species – covers aquatic organisms for human consumption, such as fish, mollusks, crustaceans, amphibians, chelonians, mammals, echinoderms, and macroalgae. These products are globally valued for their high nutritional quality, including protein content, essential fatty acids, and micronutrients, which drive strong consumer demand. However, there is also growing concern that aquafood may contain undesirable or highly toxic compounds. In this context, information has recently been circulated on social media and international media outlets highlighting concerns about **arsenic levels detected in certain aquafood species**, such as blue shark, violet shark, rays, macroalgae as well as oysters. These reports have raised apprehension regarding the potential health risks to consumers associated with the consumption of these products.

In this context, the question arises: ***should consumers be concerned about the presence of arsenic in aquafod?*** The answer is: **it depends**. It is essential to know whether we are referring to ***total arsenic, organic arsenic*** (of low toxicity), or ***inorganic arsenic*** (of high toxicity), since aquafood represents the main source of arsenic (As) exposure for many populations around the world. This distinction is crucial for accurately assessing health risks, as to date, human exposure and toxicological evaluations have focused on ***inorganic As***, while ***organic As*** has generally been considered non-toxic.

Natural and anthropogenic sources of arsenic

Arsenic is a metalloid naturally present in the Earth's crust, and it can be mobilized from mineral deposits through geological and climatic processes such as weathering, erosion, and volcanic activity. In addition to natural sources, its presence in the environment may also result from anthropogenic activities, especially due to its use in various industrial sectors, such as agriculture, through the application of herbicides, fungicides, and pesticides.

Behavior in the aquatic environment

In the aquatic environment, the degree of arsenic toxicity depends on its form, for example, inorganic or organic, and its oxidation state. The toxic and other effects of arsenical compounds on aquatic life are significantly modified by various biotic and abiotic factors, including water temperature, pH, redox potential (Eh), organic matter content, phosphate concentration, suspended solids, and the presence of other substances and toxic agents, in addition to arsenic speciation and exposure time.

Arsenic absorbed by aquatic organisms and accumulated in their bodies occurs mainly in various organic forms, with only a ***small percentage accumulated as an inorganic arsenic, which is more toxic***. The accumulation of different arsenic forms largely depends on the species and tissue analyzed. Patterns of accumulation and distribution of toxic metals in fish tissues depend on absorption and elimination rates and may cause various physiological impairments and even mortality when accumulation reaches substantially high levels.

Arsenic bioaccumulation is sensitive to the environment in which it occurs (marine, estuarine, or freshwater); it may vary among different fish species; be influenced by trophic levels in aquatic food chains; and may not be consistent across all exposure concentrations, pathways, and absorption forms.

Arsenic speciation and analytical challenges

Arsenic exists in several chemical forms that differ in their physicochemical behavior, toxicity, bioavailability, and biotransformation. The determination of these forms is an important aspect in the fields of environmental, clinical, and food chemistry. However, differentiation represents a highly complex analytical task. Various speciation procedures have been investigated, involving electrochemical, chromatographic, spectrometric, and coupled techniques. The stability of arsenic species and each step of the analytical process in speciation methods (sample collection, storage, preservation, and extraction) must be carefully evaluated.

Arsenic speciation analysis is of great importance to human health, but it poses significant challenges to analysts and remains a complex area within analytical chemistry. Comprehensive characterization of arsenic species is essential due to their different toxicological effects. The chemical nature of these compounds, particularly their tendency to alter valence states or chemical forms across a wide range of pH and redox potential conditions, hinders the assessment of their behavior and mobility in the environment.

Many studies have addressed arsenic speciation in different matrices, including a variety of extraction techniques. However, it is not possible to define a universal extraction procedure suitable for all species and matrices. The most widely used method for arsenic speciation involves separation by liquid chromatography followed by elemental detection. The choice of the most appropriate method for determining arsenic species is of great importance for obtaining reliable and accurate results.

Limitations of total arsenic-based analyses

Most of the reported data on arsenic in food describes total arsenic content, that is, the sum of all arsenic species. Total arsenic analyses that provide such data can be performed with relative ease in analytical laboratories equipped for trace element determinations. In contrast, analyses that provide information on arsenic species are much more difficult to carry out, and relatively few

Group/Species	Total Arsenic (mg/kg)	References
Freshwater fish		
Freshwater fish (raw)	0.297	Mania *et al.* (2015)
Catfish (raw)	0.043	Melo *et al.* (1999)
Carp (raw)	0.066	Melo *et al.* (1999)
Brazilian curimbatá (*Prochilodus* Sp), raw	0.030	Melo *et al.* (1999)
Brazilian matrinxã (*Brycon lundii*), raw	0.027	Melo *et al.* (1999)
Brazilian pacu (*Piaractus mesopotamicus*), raw	0.049	Melo *et al.* (1999)
Brazilian tambaqui (*Colossoma macropomum*), raw	0.043	Melo *et al.* (1999)
Tilapia (*Oreochromis niloticus*), raw	0.038	Melo *et al.* (1999)
Tilapia (raw)	0.021 - 0.038	Oliveira (2017)
Tilapia (raw)	0.014 - 0.037	Wu *et al.* (2014)
Tilapia (raw)	0.006 – 0.523	EFSA (2024)
Trout (raw)	1.020	Ruttens *et al.* (2012)
Marine fish		
Marine fish (raw)	6.960	Lewis *et al.* (2002)
Marine fish (raw)	0.230 - 3.300	Burger e Gochfeld (2005)
Marine fish (raw)	0.516	Mania *et al.* (2015)
Brazilian amberjack (*Seriola* sp.), raw	0.120 - 1.000	Silva *et al.* (2016)
Catfish (*Bagre* sp.), raw	0.110 - 1.250	Silva *et al.* (2016)
Catfish (*Bagre* sp.), raw	0.620	Silva *et al.* (2019)
Cobia (*R. canadum*), raw	1.460	Silva *et al.* (2019)
Cod (raw)	5.803	EFSA (2009)
Cod (raw)	1.705	Dahl *et al.* (2010)
Cod (frozen, 1 month)	2.008	Dahl *et al.* (2010)
Cod (frozen, 2 months)	1.788	Dahl *et al.* (2010)
Cod (cooked)	1.788	Dahl *et al.* (2010)
Cod (fried)	1.953	Dahl *et al.* (2010)
Cod (raw)	2.860	Ruttens *et al.* (2012)
Cod (raw)	0.385	EFSA (2024)
Croaker (*M. furnieri*), raw	0.950	Silva *et al.* (2019)
Flounder (raw)	9.360	Ruttens *et al.* (2012)
Grouper (*M. interstitialis*), raw	0.580	Silva *et al.* (2019)
Herring (raw)	1.930	Ruttens *et al.* (2012)
Mackerel (raw)	1.363	EFSA (2009)
Mackerel (raw)	1.390	Ruttens *et al.* (2012)
Mahi-mahi (*Coryphaena hyposaurus*), raw	0.290 - 1.180	Silva *et al.* (2016)
Mahi-mahi (*Coryphaena hyposaurus*), raw	0.580	Silva *et al.* (2019)
Mullet (raw)	0.320 - 0.600	Peshut *et al.* (2008)
Mullet (*Mugil* Sp), raw	0.010 - 0.170	Silva *et al.* (2016)
Mullet (*Mugil curema*), raw	0.160	Silva *et al.* (2019)
Salmon (raw)	2.313	EFSA (2009)

Table 1. Arsenic levels in various aquafood species (mg/kg wet weight)

Table 1. Continue

Salmon (raw)	1.018	Dahl *et al.* (2010)
Salmon (frozen, 1 month)	0.990	Dahl *et al.* (2010)
Salmon (frozen, 2 months)	0.963	Dahl *et al.* (2010)
Salmon (cooked)	0.825	Dahl *et al.* (2010)
Salmon (fried)	1.045	Dahl *et al.* (2010)
Salmon (raw)	1.050	Ruttens *et al.* (2012)
Salmon (raw)	0.124 – 0.481	EFSA (2024)
Sardine (raw)	3.040	Ruttens *et al. (2012)*
Sardine (*Sardinella brasiliensis*), raw	0.220 - 0.480	Silva *et al.* (2019)
Snapper (*Lutjanus* Sp), raw	0.240 - 0.480	Silva *et al.* (2016)
Snapper (*Lutjanus* Sp), raw	0.390 - 0.480	Silva *et al.* (2016)
Snapper (*Lutjanus* Sp), raw	0.330	Silva *et al.* (2019)
Snook (*C. undecimalis*), raw	1.070	Silva *et al.* (2019)
Tuna (raw)	1.320	EFSA (2009)
Tuna (raw)	1.430	Ruttens *et al.* (2012)
Tuna (*Thunnus* Sp), raw	0.81 - 1.80	Silva *et al.* (2016)
Tuna (*Thunnus* Sp), raw	0.49 - 1.09	Silva *et al.* (2016)
Tuna (*Thunnus* Sp), raw	0.71 - 0.94	Silva *et al.* (2016)
Tuna (*Thunnus* Sp), raw	1.300	Silva *et al.* (2019)
Tuna (raw)	1.045 – 3.383	EFSA (2024)
Shark (raw)	1.892	EFSA (2009)
Shark (various species), raw	0.130 - 1.100	Silva *et al.* (2016)
White croaker (*Cynoscion* Sp), raw	0.070 – 0.470	Silva *et al.* (2016)
Yellow croaker (*Cynoscion* Sp), raw	0.110 – 1.120	Silva *et al.* (2016)
Mollusks		
Mussel (raw)	1.669	EFSA (2009)
Mussel (raw)	3.548	Dahl *et al.* (2010)
Mussel (frozen, 1 month)	3.025	Dahl *et al.* (2010)
Mussel (frozen, 2 months)	3.273	Dahl *et al.* (2010)
Mussel (cooked)	3.355	Dahl *et al.* (2010)
Mussel (fried)	3.465	Dahl *et al.* (2010)
Mussel (raw)	2.330	Ruttens *et al.* (2012)
Mussel (*Perna canaliculus*), raw	3.250 – 4.950	Kato *et al.* (2020)
Octopus (*Octopus vulgaris*), raw	0.358	Kato *et al.* (2020)
Oyster (raw)	2.104	EFSA (2009)
Oyster (*Ostrea gigas*), raw	1.238	Liao *et al.* (2018)
Oyster (*O. gigas*, baked, 100°C, 10 min.)	1.678	Liao *et al.* (2018)
Oyster (raw)	0.005 – 0.010	Kato *et al.* (2020)
Oyster (raw)	0.798	EFSA (2024)
Oyster (*C. gigas* and *C. brasiliana*), raw	0.440 – 1.950	Vásquez-Ponce *et al.* (2025)
Algae		
Brown algae (Hijiki), raw	49.010	Park *et al.* (2019)
Brown algae (Hijiki, cooked 90°C, 5 min.)	3.430	Park *et al.* (2019)

laboratories have the capacity to generate such data. However, this information is becoming increasingly important, as ***different foods may contain different arsenic species with markedly distinct toxicities***.

Predominant forms of arsenic in food and seafood

Arsenic occurs as a natural contaminant in various foods, both in ***organic forms*** — such as arsenocholine, arsenobetaine, arsenosugars, and arsenolipids, which are generally considered to have ***low toxicity*** — and in ***inorganic forms***, being significantly more toxic and of greater concern. Inorganic arsenic species are recognized for their cumulative toxicity, with severe adverse effects on human health, including carcinogenic properties, in addition to their high bioavailability. The main route of human exposure to arsenic is through food ingestion, particularly foods of aquatic origin, which can accumulate relevant concentrations of this element.

Arsenobetaine (AsB) is the predominant form of arsenic found in marine fish and in most other seafood species. More recently, it has been demonstrated that arsenobetaine also occurs in seaweeds; however, concentrations are generally low, making its detection difficult in the presence of arsenosugars, the dominant arsenic species in algae. Arsenobetaine has not yet been detected in seawater, although it is likely to be present at trace levels. There are also several reports of arsenobetaine in freshwater organisms, although levels are generally low (<0.1 mg As/kg dry weight), much lower than those found in marine samples. The reason for the differences in arsenobetaine levels between marine and freshwater organisms is not yet fully understood, although growing evidence suggests a possible relationship with salinity, indicating that arsenobetaine may function as an osmolyte unintentionally absorbed. Freshwater fish from aquaculture may present elevated arsenobetaine concentrations due to the use of feeds formulated with marine-derived ingredients.

Arsenosugars (AsS) are generally the main arsenic constituents of seaweeds (typically 2–50 mg As/kg d.w.) and are also found at significant concentrations in animals feeding on microalgae (e.g., mussels and oysters; typically, 0.5–5 mg/kg d.w.).

Arsenolipids (AsL) are lipids containing arsenic. Although the presence of fat-soluble arsenic compounds in fish was first reported in the late 1960s, the structures of some of these arsenolipids have only recently been elucidated. In 2008, it was demonstrated that cod liver oil contains six arsenic-containing fatty acids, and that capelin oil contains three arsenic-containing hydrocarbons. Many other fat-soluble arsenic compounds were present in these two samples, but their structures remain unknown. It is very likely that arsenolipids also occur in many other fish species (particularly fatty fish such as sardine, mackerel, and tuna), as well as in other foods, although quantitative data has not yet been reported. In the fish oils examined so far, arsenolipid content ranges from 4 to 12 mg As/kg oil, which may indicate that the arsenolipid content in edible fatty fish (fish fillets) is generally somewhat below 2 mg As/kg d.w.

Impact of food processing and preparation

It is noteworthy that in publications related to arsenic levels in seafood, the information generally refers to total arsenic levels, which does not allow assessment of whether the toxic forms are present. In this regard, determining only total arsenic content does not appear to be ideal and may not be the most appropriate approach for assessing health risks, since the inorganic form is of greatest toxicological concern.

It is also important to highlight that seafood products are stored and/or processed (freezing, drying, salting, cooking, etc.) and are generally consumed after some type of preparation, such as frying or boiling. Storage and processing may potentially alter the concentration and/or the speciation profile of arsenic compounds in seafood.

In the study conducted by Dahl et al. (2010), the stability of arsenic compounds was evaluated in fresh and frozen samples of Atlantic cod (Gadus morhua), Atlantic salmon (Salmo salar), and blue mussel (Mytilus edulis) in raw, boiled, and fried forms. The results showed that total arsenic concentrations in fresh cod and salmon samples did not differ from those in frozen samples. For mussels, however, total arsenic concentration decreased significantly after storage. Inorganic arsenic was detected only in mussels and, importantly, there was no significant increase in inorganic arsenic after processing or frozen storage. Arsenobetaine accounted for 97% of total arsenic in all samples. During frozen storage, arsenobetaine content decreased significantly only in mussel samples.

Arsenic levels in aquafood species

This section reports data from national and international scientific literature on arsenic levels in different marine and freshwater species (Table 1). The studies focused mainly on total As analysis and indicate a wide variation in total arsenic levels between species and among individuals of the same species. In several cases, the values exceeded the limit established by Brazilian Health Regulatory Agency (ANVISA) for arsenic in crustaceans, bivalve mollusks, cephalopods (eviscerated), and raw, frozen, or refrigerated fish is 1.0 mg/kg (Brazil, 2022).

An important point that deserves attention is the lack of specification of the basis used — ***dry weight (d.w.) or wet weight (w.w.)*** – in scientific publications on arsenic in seafood. When results do not indicate the basis, there is a risk of overestimating or underestimating the metal concentration, which compromises both health risk assessment and comparison with legal limits. For example, a value expressed in mg/kg dry weight may appear three to four times higher than it would be on a wet weight basis, leading to misleading conclusions about food safety.

In addition, the absence of this information hampers comparison across different studies since each work may adopt a different basis. This undermines the consolidation of information on arsenic occurrence in various seafood species and prevents consistent analyses of dietary exposure and toxicological impacts. Therefore, clearly stating the basis used is essential to ensure accuracy, transparency, and reliability in food chemical analysis results.

In fact, even the Brazilian Normative (Brazil, 2022), which establishes maximum tolerable limits (MTLs) for contaminants in food, including arsenic in seafood, does not specify the basis used. This omission may create ambiguities in the interpretation and application of the limits.

Nevertheless, in most studies related to dietary arsenic intake, analyses focus on the quantification of total arsenic rather than specifically distinguishing inorganic arsenic. This approach limits the assessment of results against toxicological reference values, which are predominantly based on the more toxic inorganic forms. Furthermore, ***studies evaluating inorganic arsenic levels in raw seafood products do not provide adequate estimates of actual intake, as most of these foods undergo cooking processes before consumption***. Such processes can lead to significant changes – both increases and decreases – in the concentration and distribution of different arsenic species, making it impossible to directly extrapolate data obtained from raw samples to accurate dietary exposure estimates.

Dietary Exposure to Arsenic

According to the International Agency for Research on Cancer (IARC, 2012), the main route of arsenic exposure for the general population is the ingestion of contaminated food or water, with an estimated daily intake ranging from 20 to 300 µg/day. Low levels of inorganic and organic arsenic are found in most foods (<0.25 mg/kg), influenced by the type of food (seafood vs. meat or dairy), cultivation conditions (soil, water, pesticide use), and processing techniques.

The highest arsenic concentrations occur in seafood (2.4–16.7 mg/kg in marine fish, 3.5 mg/kg in mussels, and >100 mg/kg in certain crustaceans), followed by meat, cereals, vegetables, fruits, and dairy. Inorganic arsenic predominates in meat, poultry, dairy, and cereals, whereas organic arsenic (e.g., arsenobetaine) predominates in seafood, fruits, and vegetables.

According to the European Food Safety Authority (EFSA, 2009), the proportion of inorganic arsenic in fish and other seafood species is small and tends to decrease as total arsenic content increases. Fixed values of 0.03 mg/kg for fish and 0.1 mg/kg for other seafood species were considered realistic for dietary exposure estimates.

The Joint FAO/WHO Expert Committee on Food Additives (JECFA) determined that the lower benchmark dose limit for a 0.5% increase in lung cancer incidence (BMDL0.5) is 3.0 µg/kg body weight/day (range: 2–7 µg/kg/day), considering total dietary exposure (FAO/WHO, 2010).

Regional differences in daily arsenic intake primarily reflect seafood consumption, being higher in Japan than in Europe or the USA. Approximately 25% of daily arsenic intake is estimated to be inorganic. Intake tends to be higher in men than in women and children, ranging from 1.3 µg/day in infants <1 year to 13 µg/day in men aged 60–65 years. Based on data from 19 European countries, exposure to inorganic arsenic from food and water was estimated at 0.13–0.56 µg/kg body weight/day for average consumers and 0.37–1.22 µg/kg/day for the 95th percentile consumers (those whose intake is among the highest 5% of the assessed population).

In humans, ***soluble inorganic arsenic is almost completely absorbed after ingestion***. Absorption of different organic arsenic forms is generally above 70%. Once absorbed, arsenic is widely distributed to virtually all organs. Prolonged intake of inorganic arsenic in humans has been associated with skin lesions, cancer, neurotoxicity, cardiovascular disease, alterations in glucose metabolism, and diabetes. Emerging evidence suggests negative impacts on fetal and infant development, particularly reduced birth weight, highlighting the need for more data on dose-response relationships and critical exposure periods for these effects.

Arsenobetaine, the main form of arsenic present in fish and most seafood species, is not metabolized by the human body and is excreted unchanged. For this reason, it is widely recognized as a form of arsenic with no toxicological relevance. In humans, arsenosugars and arsenolipids are mainly metabolized to dimethylarsinate, but specific toxicity information is not available. For other organoarsenical compounds, human toxicity data are lacking.

Given the variability in arsenic species composition in foods, EFSA has recommended that exposure to inorganic arsenic be reduced to the lowest possible level. In addition, the importance of further studies on the toxicity and bioavailability of other arsenic forms, such as arsenolipids and arsenosugars, was emphasized, as well as the need to improve analytical methodologies for

determining different arsenic species in foods.

Misleading or decontextualized reporting can cause unnecessary public alarm

Brazil is highlighted as an important seafood importer and exporter with countries and regions such as Asia, Europe, Russia, China, Vietnam, Canada, the USA, Peru, Chile, Argentina, Uruguay, among others. The country enforces strict regulations regarding the identity and quality standards that seafood must meet, both for import and export.

In the controversial study conducted by Vásquez-Ponce et al. (2025), which alarmed the Brazilian population and importers of Brazilian seafood via social media and newspapers, the authors ***highlighted potential public health risks associated with the consumption of raw oysters, particularly their role in the bioaccumulation of potentially toxic metals***. The study assessed total arsenic levels in oysters (Crassostrea gigas and Crassostrea brasiliana) collected from five markets in the states of São Paulo and Santa Catarina (winter 2022 and summer 2023). Total arsenic concentrations (mg/kg wet weight) varied by location and season – Cananéia (0.44 and 0.49 mg/kg), Santos (0.74 and 0.91), São Paulo (0.91 and 1.86), Florianópolis (1.01 and 1.95), and Peruíbe (1.57), respectively. Although total arsenic concentrations were elevated, the authors ***emphasized the need for a more precise quantification of inorganic (toxic) arsenic species to better assess potential human health risks, since the main form of arsenic present in marine fish and most other seafood species is organic, which has lower toxic potential***.

However, news reports shared inaccurately led to alarming headlines, such as: ***"Oysters sold in Brazil accumulate arsenic and carry antibiotic-resistant bacteria, study finds" – "Study shows Brazilian oysters are contaminated with arsenic" – "Brazilian oysters are contaminated with arsenic, study says" – "Study finds arsenic in Brazilian oysters" – "A recent study revealed that some oysters may come 'filled' with arsenic and multidrug-resistant bacteria" – "Brazilian oysters are contaminated with arsenic and superbugs, reveals unprecedented study" – "Oysters sold in Brazil contain bacteria and toxic metals, study says" – "Oysters sold in Brazil carry multidrug-resistant bacteria and toxic metal…"*** — among others.

It is important to clarify that the study was conducted only on oyster samples collected from the states of São Paulo and Santa Catarina, and the results cannot be generalized to the entire national production. Misleading or decontextualized news can spread misinformation and create unnecessary public alarm (or panic). It is important to remember that regulatory authorities exist to protect public health by ensuring that only products meeting food safety standards reach consumers. Inaccurate or poorly contextualized reporting can therefore provoke unnecessary concern and erode public trust in these oversight institutions.

It should be reiterated that the quantification of ***"total arsenic"*** corresponds to the sum of all arsenic species present in the sample, including both inorganic arsenic (toxicologically relevant) and organic forms such as arsenobetaine, which is considered non-toxic to humans. Thus, even if a particular seafood species shows high total arsenic concentrations – exceeding the 1.00 mg/kg limit established by ANVISA – this value may largely reflect the presence of arsenobetaine, which predominates in marine organisms, while inorganic arsenic levels remain low. Under these circumstances, using total arsenic alone as a regulatory criterion can lead to misinterpretations regarding the actual toxicological risk to consumers, compromising decision-making about food safety. Therefore, the exclusive determination of total arsenic is not a reliable indicator of toxicological risk, as it does not allow distinction between toxic and non-toxic forms of the element.

Conclusion

The presence of arsenic in foods, particularly those of aquatic origin, constitutes a significant food safety concern due to the toxicity associated with inorganic forms of this element. However, proper interpretation of the data requires differentiation between chemical forms, as most arsenic in seafood occurs in low-toxicity organic forms, such as arsenobetaine.

The absence of information regarding the basis used – dry weight (d.w.) or wet weight (w.w.) – in scientific publications on arsenic in seafood complicates comparisons between studies, as each may adopt a different basis. This can hinder the consolidation of information on arsenic presence across various seafood species and prevent consistent analyses of dietary exposure and toxicological impacts. Therefore, clearly reporting the basis used is essential to ensure accuracy, transparency, and reliability in chemical food analyses.

The predominance of studies based solely on ***total arsenic***

quantification also limits the precision of human health risk estimates. Furthermore, processing (e.g., freezing or cooking) and culinary preparation can alter arsenic speciation and concentration, highlighting the need to consider foods in the form in which they are consumed. The adoption of specific analytical methodologies and standardized protocols for chemical speciation is also essential to support public policies, regulatory actions, and consumer guidance based on robust scientific evidence.

In this context, it is critical to emphasize that the dissemination of misleading or decontextualized news can distort scientific findings and generate unwarranted public alarm, undermining trust in institutions and hindering technical dialogue with society.

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A Review on the Aquaculture Stewardship Council (ASC): Origins, Evolution, and Global Position in the Seafood Industry

Introduction

Seafood is one of the fastest-growing protein sources in the world, with aquaculture now providing more than half of all fish consumed globally. As aquaculture expanded, concerns over environmental impacts, labor conditions, and consumer trust grew stronger. In response, the Aquaculture Stewardship Council (ASC) emerged as a global certification body to ensure that farmed seafood is produced responsibly, transparently, and sustainably. Today, ASC is widely regarded as the leading international label for responsibly farmed seafood.

How ASC Started

The ASC was officially founded in 2010 by the World-Wide Fund for Nature (WWF) and the Dutch Sustainable Trade Initiative (IDH). Its creation was the result of a multi-year process known as the Aquaculture Dialogues (2004-2010), which brought together farmers, NGOs, scientists, retailers, and other stakeholders to develop measurable sustainability standards. These dialogues led to species-specific benchmarks for fish and shellfish such as tilapia, pangasius, abalone, and shrimp.

In 2012, ASC launched its recognizable green consumer label, and the first certified farms (a tilapia farm in Indonesia and a pangasius farm in Vietnam) began supplying products under ASC standards. This marked the beginning of ASC's role in shaping the global seafood certification landscape.

Progress and Expansion

Over the past decade, ASC has grown into a globally recognized certification scheme. It now covers 58 species groups across 52 countries, including major aquaculture products like salmon, shrimp, mussels, trout, cobia, and seaweed (developed jointly with the Marine Stewardship Council).

ASC standards address seven core areas:

1. Legal compliance
2. Environmental impact
3. Fish health and welfare
4. Responsible feed sourcing
5. Social responsibility and fair labor
6. Community engagement
7. Transparency and continuous improvement

The organization's credibility is reinforced through independent third-party audits, membership in the ISEAL Alliance, and recognition by the Global Sustainable Seafood Initiative (GSSI).

Position in the Seafood World

ASC is now one of the most trusted and recognized farmed seafood labels, alongside MSC (Marine Stewardship council). The MSC is ASC's counterpart for wild-caught fisheries. Founded in 1997, the MSC developed global standards for sustainable fishing and remains the most recognized ecolabel for wild seafood. While ASC focuses on aquaculture, MSC certifies fisheries that are managed responsibly and protect marine ecosystems. Together, ASC and MSC cover both farmed and wild seafood, offering consumers a complete sustainability assurance across the seafood sector.

To ensure the integrity of certified seafood, the MSC and the ASC operate a shared Chain of Custody (CoC) certification system. This standard applies to all companies handling certified seafood after it leaves the farm or fishery — including processing plants, traders, wholesalers, distributors, and retailers.

The Chain of Custody certification assures businesses and consumers that:

1. Certified products are kept separate from non-certified products at every stage.
2. Traceability is maintained through detailed documentation and third-party audits.
3. Companies in the supply chain are working according to strict, internationally recognized standards.

This system not only builds consumer trust in the ASC and MSC labels but also provides assurance to supply chain actors that they are operating responsibly and meeting market expectations for transparency and sustainability.

Major retailers, foodservice companies, and even cruise lines like Holland America Line source ASC-certified seafood to meet consumer demand for sustainability.

Consumer surveys consistently rank ASC as the most trusted farmed seafood label, with campaigns such as Sustainable Seafood Week raising awareness in markets like Japan, Europe, and North America. In salmon farming alone, around 30% of global production now carries ASC certification, a remarkable achievement within just over a decade.

Innovations and New Standards

ASC has continuously expanded its scope:

- Feed Standard (2021): Ensures aquafeed ingredients are sourced responsibly.
- Improver Programme (2023): Helps farms transition toward certification.
- Unified ASC Farm Standard (2025): Replaces species-specific rules with a comprehensive framework built around four pillars: Fish, Farm, People, Planet.

These developments ensure ASC remains adaptable and forward-looking, addressing issues such as climate change, biodiversity, and labor rights.

Criticisms and Challenges

Like any certification, ASC has faced criticism. Some NGOs and journalists have questioned whether certain certified farms, especially in the salmon sector, truly meet sustainability expectations - citing issues like stocking densities, escapes, or antibiotic use. ASC acknowledges these challenges and regularly revises its standards, with a major update scheduled for 2025. This openness to scrutiny highlights ASC's commitment to continuous improvement.

Conclusion

In just 15 years, the Aquaculture Stewardship Council has evolved from a WWF-IDH initiative into a global benchmark for responsible aquaculture. It has given consumers' confidence in farmed seafood, encouraged producers to improve practices, and set a high bar for sustainability in the industry. While challenges remain, ASC's growing influence signals that responsible aquaculture is no longer optional but essential for the future of seafood.

Interview with Hon. Professor Roy D. Palmer

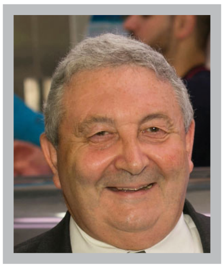
Biography:

Professor Roy Palmer (Australia) is an internationally recognized leader in the seafood and aquaculture sectors, with decades of experience spanning industry, research, and global development initiatives.

He is currently Founder & CEO Seafood Consumers Association Ltd; Profesor Honorario at Universidad Tecnológica del Mar de Tamaulipas Bicentenario and Deputy Chair, Aquaculture without Frontiers.

He has been bestowed with the World Aquaculture Society (WAS) Honorary Life Award and the World Gastronomy Institute (WGI) Medal of Honor amongst many awards over the years.

He is the Founder, Association of International Seafood Professionals; served as President of the World Aquaculture Society (WAS) Asian Pacific Chapter and WAS Board; worked for FAO (Senior Consumer Behaviour Expert), The World Bank (TransFORM project) and the Australian Seafood Cooperative Research Centre (Principle Investigator & Industry Education Manager); engaged by the Mexican Government to assist Conapesca in successfully increasing seafood consumption in Mexico and throughout his career, he has actively promoted the seafood industry at local and international levels.



Could you tell us about your professional journey and how you became involved in the seafood and aquaculture sector?

In 1972 I started my seafood career with Wales, Kerville & Co (importers/exporters) in Melbourne, Australia where, by good fortune, I met my wife Gabrielle – we have recently celebrated our 50th wedding anniversary.

It was my first job in Australia, and my role was rich and varied and I met a variety of nationalities who also centered on seafood as it was generally unregulated, and it was a 'nil level entry' industry – no qualifications needed, just a work ethic!

Initially this was 'just a job' to get a start in Australia but I fell in love with seafood, its people and its benefits and opportunities and hence it became a voyage – I had no specific plans to start with.

What inspired you to dedicate your career to seafood, and what do you consider as the turning point in your professional life?

I had arrived in Australia as a willing migrant from England. The plan was to stay for 2 years then return to the United Kingdom, but I met the girl that became my life partner and my company offered to pay for my promised UK return (a promise to my parents) as long as went for a holiday/business trip and returned.

That was probably the first ‘turning point’. After that there were many such ‘light bulb’ moments that changed my vocational path.

Three issues probably stand out – travel, training and teams – the Three Ts.

Travel broadens the mind. In Australia the market is now 28 million people – there are more people in Tokyo and, of course, Australia is a massive country. Jet travel from Melbourne to Perth is 5 hours and to Darwin is similar. Road travel from Melbourne to Sydney is 10-12 hours and to Adelaide 8-9 hours. 60% of people live in Melbourne and Sydney and overall, 70% of people live in cities. When you are trying to sell seafood in Australia your focus is on those centres.

I secured my first overseas role in 1978 – our business had aligned with a Boston, USA seafood importer and a Hong Kong seafood trading company and I was offered the role of managing the entity.

It was at the end of the Viet Nam War (or the American War in Vietnam as some say) and USA had banned seafood from Viet Nam for some years. Slowly and surely excellent Viet Nam seafood started finding a home through Hong Kong to USA.

Simultaneously, Thailand’s seafood sector was undergoing rapid industrialization and export-driven growth, especially in shrimp and tuna processing, fueled by foreign investment and modernization of fishing methods. By the early 1980s, Thailand was becoming a key player in canned tuna and shrimp exports, establishing itself as a major global seafood supplier.

My world changed immensely. I was working very hard and learning so much about world trade in seafood. In Australia we would have had to think twice about buying a 20-foot container, but our American and EU buyers thought nothing about 5 x 40-foot containers. Exciting times!

I came back from this venture with different perspectives. Traveling and meeting people, networking with your peers is such an essential element of growth.

When it came to Training, I was typically a person who had been in the industry for around 30 years and had taught myself on the journey. I had experienced several roles, and I thought I knew as much as you needed to know.

That had started to unravel in about 1995 when I was Deputy Chair of SeaQual, an industry and government approach to quality in seafood. This then led to the need of a vocational training program for seafood. I was engaged as a post-harvest specialist and went on to be Deputy Chair of Seafood Training Australia where by 2000 we had created the National Seafood Industry Training Package.

The National Seafood Industry Training Package is a nationally endorsed curriculum providing robust vocational education, skills, and standards for Australia’s seafood sector—including aquaculture, fishing operations, seafood processing, compliance, sales, and distribution. Its importance lies in ensuring a highly skilled, adaptable workforce that meets contemporary industry needs, supports best practice, and enhances productivity, safety, and sustainability throughout the seafood value chain. The package fosters continuous improvement and lifelong learning, helping Australia maintain world-class standards and global competitiveness across all seafood disciplines.

I walked the walk…. I became an official Seafood Trainer by obtaining Certificate IV in Training and Assessment and Diploma of Seafood Processing. Additionally, the company I owned won the inaugural Australian Seafood Training Award.

I continue to push my educational barriers having achieved this year Graduate Certificate in Management and Diploma in Marketing Management on my journey to achieve Master of Business Administration, hopefully early 2026.

Finally, Team over individual approach.

Teams outperform individuals because they bring together diverse skills, perspectives, and strengths, enabling more effective problem-solving and innovation.

Collaborative teamwork promotes shared responsibility, reduces burnout, and boosts productivity by dividing tasks based on members’ expertise.

Strong teams foster better communication and trust, creating a supportive environment where members motivate each other and contribute to common goals.

In contrast, focusing solely on individual performance overlooks the power of collective effort and can hinder creativity and cohesion. Ultimately, successful teams combine individual talents with a shared purpose, achieving results that far exceed what individuals can accomplish alone.

In your view, why is seafood one of the most critical elements of global food security in the future?

Acceptance and political will for aquaculture is essential.

Aquaculture has become essential for ensuring global food security as land and water constraints, climate change, and environmental degradation threaten traditional agriculture’s ability to meet growing nutritional needs. With wild fisheries maximised and world population projected to reach ten billion by 2050, there is increasing need internationally on the acceptance that farmed seafood offers a sustainable pathway to feed billions without exhausting terrestrial resources. The World Bank and UN agencies repeatedly emphasize that aquaculture can provide affordable, protein-rich food with lower greenhouse gas emissions and reduced land use compared to livestock or crops.

Yet the future of aquaculture—and global food security—hinges on political will. Governments must prioritize the development of responsible aquaculture through supportive policies, investment in research and infrastructure, and transparent regulatory frameworks. Building public trust, incentivizing sustainable practices, and integrating aquaculture into national food strategies will drive the sector’s acceptance and growth. Only with clear political support and international cooperation can aquaculture fulfil its promise as an engine for nutritious, resilient, and equitable food supplies in the decades ahead.

How do you compare global perspectives on seafood consumption and production across different regions, such as Asia, Europe, and Australia?

Global perspectives on seafood consumption and production vary markedly across regions such as Asia, Europe, and Australia, shaped by cultural preferences, resource availability, and sustainability priorities.

Asia

Asia is the world leader in seafood consumption and production, with countries like China, Japan, Vietnam, and

Thailand at the forefront. Per capita seafood intake in parts of Southeast Asia far exceeds global averages, with fish, crustaceans, and molluscs featuring prominently in daily diets. This region has seen explosive growth in aquaculture, especially in China, which produces more farmed seafood than any other nation and relies on both domestic demand and exports for global market integration. Cultural acceptance is high, seafood is integral to traditional cuisines, and aquaculture is essential for food security and economic growth.

Europe

Europe's consumption patterns are more varied, with Western European countries like Portugal, Spain, France, and Denmark consuming much more seafood than Eastern Europe. European consumers show rising interest in sustainability, food traceability, and ethical sourcing. Aquaculture is well-established, particularly in salmon farming in Norway and Scotland, though wild catch remains a significant part of the supply chain. EU policies strongly promote responsible fishing, marine ecosystem protection, and product labelling, shaping consumer awareness and production practices.

Australia

Australians consume seafood at moderate but stable rates—about 15 kg per capita—primarily fish (tuna, salmon, trout), crustaceans (prawns, lobsters, crabs), and molluscs (oysters, squid, abalone). The sector emphasizes sustainability, environmental stewardship, and strict fisheries management, with growing attention to aquaculture to relieve pressure on wild stocks and meet demand. Multicultural influences widen the variety of cuisines, and premium, traceable Australian seafood is highly valued domestically and for export, especially to Asia.

In Summary

Globally, Asia leads in both consumption and production, driven by strong cultural ties and aquaculture growth; Europe displays regional diversity and leads in sustainability; Australia is marked by a balance of sustainability, premium positioning, and evolving consumer preferences—each region reflecting its unique history, resources, and policy priorities.

What do you see as the main challenges currently facing the seafood industry worldwide?

I have often spoken about Aquaculture, and it being run internationally like FIFA runs football (the concept of one set of rules).

A unified global standard for the seafood industry represents a transformative vision—one where producers, processors, retailers, and consumers all operate with shared trust, transparency, and responsibility. Under a single, universally recognized framework, the full supply chain would be held to rigorous benchmarks for sustainability, food safety, labor rights, animal welfare, and traceability.

Such a standard would close gaps in existing certifications, reduce confusion for buyers and consumers, and streamline compliance for producers regardless of geography or production method. With interoperable digital traceability, every stage—from catch or farm to shelf—would be documented and verifiable, empowering consumers to make informed choices while combating fraud and illegal, unreported, or unsustainable practices.

Industry-wide adoption of one standard would also drive continuous improvement, lower barriers to market access, and facilitate international trade by assuring regulators and trading partners of best practice compliance. Ultimately, bringing the seafood sector together under a single, comprehensive standard would support a more resilient, ethical, and sustainable global seafood system—delivering benefits for seafood workers, ocean health, and communities everywhere.

You have collaborated with international organizations and countries across the globe. Could you share some experiences that you believe are particularly inspiring or influential?

I played an influential role in assisting the Mexican government, specifically through CONAPESCA (the National Commission of Aquaculture and Fisheries), to increase seafood consumption in Mexico.

Mexico has launched significant campaigns to promote its fishery and aquaculture products, aiming to raise seafood consumption per capita, with emphasis on nutritious and affordable local species like tilapia, trout, and squid. My work included strategic advocacy, outreach to consumers and policymakers, and developing innovative approaches to reposition seafood as a vital protein source for health and food security.

Under CONAPESCA's leadership (Mario Aguilar Sanchez), supported by experts like me, Mexico implemented national programs that combine public policy, education, and market development to expand domestic seafood demand while improving aquaculture productivity and sustainability. These efforts align with global food security goals and highlight how government and industry collaboration can successfully promote seafood consumption in developing countries.

My expertise in post-harvest practices, seafood safety, nutrition, and international promotion was acknowledged by CONAPESCA as being instrumental in shaping Mexico's approach, serving as a model of effective partnership between government and global seafood advocates to elevate seafood's role in national diets and economies.

We had a goal for 5 years, but we achieved it in 3 years, and I had the great honour of representing Mexico at an FAO COFI event in Rome, Italy where we detailed the program. What stood out was Walmart, largest retailer in Mexico, who had initially stood aside from involvement in the project stating they had to change their mind and alter all their seafood space to accommodate the increased demand!

Is there a project or initiative you are especially proud of, which could serve as a model for other nations?

There are many ……here is one

My role in Aquaculture without Frontiers continues. I have had a close affinity with Universidad Tecnológica del Mar de Tamaulipas Bicentenario (UTMarT) since 2013.

I was the catalyst with Antonio Garza de Yta in the significant involvement with Aquaculture without Frontiers (AwF) and the UTMarT in advancing sustainable aquaculture initiatives, including the creation of an oyster industry in Tamaulipas, Mexico. AwF's approach in Tamaulipas centers around establishing Aquaculture Learning Centers (ALCs) to educate students and practitioners, fostering sustainable aquaculture practices to improve local livelihoods and food security.

At the Tancol site in Tamaulipas, AwF collaborated with UTMarT to utilize existing freshwater resources and infrastructure, including large tanks for research and training on shellfish aquaculture, especially oysters. Early engagement by AwF volunteers provided technical training on shellfish hatchery processes and microalgae cultivation, which are essential for oyster farming success. The initiative aimed to replace failed fishing methods currently used in Laguna Morales with sustainable oyster aquaculture, offering fisherfolk a viable, environmentally friendly alternative income source.

Our leadership, combined with institutional support from UTMarT and local governments, has helped to lay the foundation for a thriving oyster sector in Tamaulipas that integrates community livelihoods, sustainability, and economic development.

This collaboration exemplifies successful partnership between academic institutions, NGO initiatives, and government agencies in fostering aquaculture innovations that address malnutrition and poverty while protecting marine environments.

How important are education and consumer awareness in shaping sustainable seafood production and consumption?

Education and consumer awareness are fundamental drivers in shaping sustainable seafood production and consumption. Informed consumers create demand for responsibly sourced, environmentally friendly, and ethically produced seafood, which in turn incentivizes producers and the industry to adopt sustainable practices.

When consumers understand the environmental impacts of overfishing, habitat destruction, and seafood fraud, they tend to prefer seafood with verified sustainability certifications and transparent supply chains, driving market transformation toward more sustainable options. Education also demystifies complex concepts such as traceability, fishing quotas, and aquaculture methods, empowering consumers to make choices that support ocean health and long-term seafood availability.

On the production side, education equips fishers, farmers, processors, and retailers with knowledge on best practices, regulatory compliance, and innovative sustainability solutions. Consumer awareness campaigns and seafood literacy programs amplify demand signals for sustainable products, creating a virtuous cycle where production and consumption align with conservation goals, social equity, and economic viability.

Without robust education and consumer engagement, sustainable seafood initiatives struggle to gain traction. These efforts are critical for bridging gaps between industry, regulators, and consumers to ensure seafood systems remain resilient, equitable, and environmentally responsible for future generations.

What actions should policymakers prioritize to promote responsible growth in the seafood industry?

Policymakers should prioritize the following actions to promote responsible growth in the seafood industry:

1. Strengthen Sustainable Fisheries Management: Implement science-based catch limits, monitoring, and enforcement to prevent overfishing and ensure healthy fish stocks for the long term.

2. Support Sustainable Aquaculture Development: Encourage environmentally responsible farming practices, innovation, and infrastructure investment to reduce pressure on wild stocks while meeting demand.

3. Enhance Supply Chain Transparency and Traceability: Mandate clear labeling and adopt digital traceability systems to combat seafood fraud, promote consumer trust, and ensure accountability.

4. Promote Consumer Education and Awareness: Invest in public campaigns that inform consumers about sustainable seafood choices and the health and environmental benefits of responsible consumption.

5. Protect Marine Ecosystems: Enforce regulations to reduce habitat destruction, bycatch, and pollution associated with fishing and aquaculture activities.

6. Foster Fair Labor Practices: Implement and monitor labor standards to eliminate forced labor, improve working conditions, and uphold human rights in seafood supply chains.

7. Encourage Research and Data Sharing: Fund scientific research to improve fisheries stock assessment, aquaculture technologies, and socio-economic studies to guide policy making.

8. Facilitate International Cooperation: Collaborate with global partners to address transboundary fisheries issues, trade regulations, and sustainable seafood certification standards.

By focusing on these priorities, policymakers can balance economic growth with environmental stewardship and social responsibility in the seafood sector.

Once they have established the boundaries the bureaucracy needs to step back and allow the industry to get on with its activities within those boundaries.

From an environmental standpoint, what measures are most urgent to ensure the protection of marine ecosystems while supporting aquaculture?

From an environmental standpoint, the most urgent measures to protect marine ecosystems while supporting aquaculture should include:

1. Implementing Site Selection and Zoning: Establish aquaculture zones away from ecologically sensitive areas such as coral reefs, mangroves, and seagrass beds to prevent habitat destruction and preserve biodiversity.

2. Promoting Sustainable Feed Practices: Reduce reliance on wild-caught fish meal and oil in aquaculture feeds by developing alternative, eco-friendly feed ingredients to lessen pressure on wild fish stocks. Create more opportunity for herbivore species rather than carnivore species.

3. Controlling Nutrient and Waste Discharges: Employ advanced waste management technologies to minimize nutrient pollution, eutrophication, and sedimentation that can degrade surrounding marine environments. Clean water is essential!

4. Preventing Disease and Escapees: Enforce stringent biosecurity measures and use barrier technologies to reduce disease outbreaks and prevent farmed species from escaping into the wild and disrupting native ecosystems.

5. Monitoring and Adaptive Management: Establish continuous environmental monitoring programs to detect and mitigate aquaculture's ecological impacts promptly, allowing regulatory frameworks to adapt based on scientific evidence. Strong collaboration required. Data, data, data ….

6. Encouraging Integrated Multi-Trophic Aquaculture (IMTA): Promote IMTA approaches that combine different species (e.g., fish, shellfish, seaweed) to recycle nutrients naturally and enhance ecosystem resilience.

7. Supporting Research and Capacity Building: Invest in scientific innovations and stakeholder training to develop best practices that balance production efficiency with ecosystem conservation. Data is king, benchmarking is helpful.

These measures are critical to achieving aquaculture growth without compromising marine ecosystem health, ensuring both environmental sustainability and industry viability.

How do you envision the future of the seafood industry in the next 10–20 years?

Here is the Vision/Mision and Core Values I am driving at Seafood Consumer Association

Vision

Empowered, informed seafood consumers driving a fair, sustainable, healthy and transparent seafood future.

Mission

To educate, advocate and represent seafood consumers in Australia and globally by promoting transparency, responsible sustainability, affordability, food security, and ethical practices in the seafood sector.

Core Values

- Integrity in advocacy
- Transparency and accountability
- Consumer empowerment through education
- Equity and fairness across the supply chain
- Commitment to responsible environmental and social sustainability

What opportunities do you see for developing countries, including Iran, in advancing their seafood and aquaculture sectors?

Developing countries, including Iran, have significant opportunities to advance their seafood and aquaculture sectors by leveraging their natural resources, growing markets, and technological innovation. Key opportunities include:

1. Sustainable Aquaculture Expansion: Developing countries often have abundant coastal and freshwater resources suitable for aquaculture growth. Iran can expand species diversification, adopting sustainable farming techniques to increase production while minimizing environmental impacts.

2. Value Addition and Processing: Improving post-harvest processing, cold chains, and value-added seafood products can boost shelf life, reduce waste, and open higher-value markets domestically and internationally. Increase your seafood consumption by including seafood consumers and creating great consumer experiences.

3. Technology Adoption: Introducing modern aquaculture technologies such as recirculating aquaculture systems (RAS), bio floc technology, and digital monitoring can improve yields, disease control, and resource efficiency.

4. Capacity Building and Training: Investing in education, vocational training, and extension services for fishers, farmers, and processors strengthens sector professionalism—and encourages adoption of best practices. Instigate my TTT program – Travel, Training and Teams!

5. Market Access and Trade Facilitation: Developing countries can capitalize on growing global seafood demand by improving product quality, certification compliance, and planning infrastructure to meet export market standards.

6. Policy and Regulatory Frameworks: Iran and similar countries can establish clear, science-based policies and regulatory systems that support sustainable growth, environmental protection, and food safety. Try and build on what is already out there rather than building from scratch.

7. Public-Private Partnerships: Collaboration between governments, private sector, NGOs, and research institutions can mobilize resources and innovation for sector development.

By embracing these strategies, developing countries can enhance food security, create employment, and build resilient aquatic food systems integrated into the global seafood economy.

Finally, what message would you like to share with the next generation of researchers, entrepreneurs, and leaders in seafood and aquaculture?

Get involved, make a commitment, and get the right attitude. You could be the smartest person on earth but if you do not have the right attitude (such as getting to a meeting on time, under-promising and over-delivering, taking an interest), then you will find it difficult to succeed in the seafood world. Never stand on your laurels. Ask questions, even if they appear silly, and please push the envelope!

Follow my Travel, Train and Team (TTT) philosophy – travel as widely as you can, work hard on your education (never stop learning) and understand that success is about working as a team.

Professor Palmer, thank you for sharing your expertise with Future Aquaculture. Your perspectives will provide invaluable guidance and inspiration to our international audience.

Seafood Consumers Association

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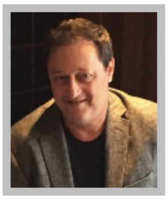

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Solid-State Fermentation of Agricultural By-products for Sustainable Tilapia and Vannamei Shrimp Aquaculture: A Review of Processes, Benefits, and Future Prospects

1. Introduction

The global aquaculture sector has undergone exponential growth, with Nile tilapia and vannamei shrimp emerging as two of the most significant contributors to aquatic food production. As of 2020, annual production exceeded 6 million metric tonnes for tilapia and 5.8 million for vannamei shrimp, highlighting their role in meeting global protein demands (FAO, 2022). Despite this success, the industry's economic sustainability is perpetually challenged by feed costs, which constitute 50-70% of total operational expenses (Tacon & Metian, 2015). The industry's historical reliance on fishmeal as a primary protein source is environmentally and economically untenable due to overfishing, price volatility (approx. $1,730/tonne in 2024), and competition with other livestock sectors (Naylor et al., 2021).

This has spurred extensive research into alternative, locally sourced feed ingredients. Agricultural by-products, such as rice bran in Asia, soybean and corn residues in Latin America, or wheat bran in the rest of the world are abundant and inexpensive in major aquaculture-producing regions. While rich in carbohydrates, proteins, and fibers, their direct use is often limited by poor digestibility, low nutrient bioavailability, and the presence of anti-nutritional factors (ANFs) like phytates, toxins, tannins, and protease inhibitors (Francis, Makkar, & Becker, 2001).

Solid-state fermentation (SSF) offers a robust biotechnological solution to these limitations (Zimmermann et. al, 2023). SSF is a process where microorganisms are cultivated on solid substrates with minimal free water, mimicking natural decomposition (Pandey, 2003). This process utilizes fungi (e.g., Aspergillus niger, A. oryzae), bacteria (e.g., Bacillus subtilis, Lactobacillus plantarum), or yeasts to enzymatically break down complex biopolymers, detoxify ANFs, synthesize essential nutrients, and enrich the protein content of the substrate (Singhania et al., 2009). The resulting "pre-digested" fermented product exhibits enhanced nutritional value and digestibility.

This review synthesizes current knowledge on the application of SSF for valorizing agricultural wastes into high-quality feeds for tilapia and vannamei shrimp. It evaluates the documented benefits, implementation challenges, and future technological directions, providing a comprehensive overview of its potential to foster a more sustainable and resilient aquaculture industry.

2. Solid-State Fermentation: Process and Nutrient Valorization

SSF is a controlled microbial process designed to enhance the nutritional profile of solid organic substrates.

2.1 Key Processes and Microorganisms

The SSF process typically involves three main stages:

• **Substrate Preparation:** Raw materials such as rice bran (12-14% protein), wheat bran (16% protein), or soybean meal are ground to increase surface area and moistened to a specific level (typically 40-60%) to support microbial growth without creating an anaerobic slurry (Ashok, Doriya, & Rao, 2018).

• **Inoculation:** The substrate is inoculated with selected microbial strains. Common choices include proteolytic bacteria like ***Bacillus subtilis***, lactic acid bacteria such as ***Lactobacillus plantarum*** (which lowers pH, inhibiting pathogens), and cellulolytic fungi like ***Aspergillus niger or Trichoderma reesei*** (Ramachandran, Bairagi, & Ray, 2005). The use of microbial consortia, such as L. plantarum combined with Saccharomyces cerevisiae, can enhance fermentation efficiency through synergistic interactions (Oboh, 2006).

• **Fermentation:** The inoculated substrate is incubated under controlled conditions (temperature 25-40°C, pH 4-7) for 24-72 hours. During this period, microorganisms secrete a suite of extracellular enzymes (e.g., proteases, amylases, cellulases, phytases) that break down complex macromolecules.

2.2 Nutrient Valorization

The biochemical changes during SSF lead to significant nutritional enhancement through several key mechanisms:

• **Protein Enrichment and Hydrolysis:** Microbial biomass growth converts non-protein nitrogen and complex organic nitrogen from the substrate (including aquaculture sludges) into high-quality microbial protein. This bioconversion involves the enzymatic breakdown of large protein molecules into more readily absorbable free amino acids and peptides (Bairagi, Ghosh, Sen, & Ray, 2002). For example, FSBM consistently exhibits a 20-30% increase in crude protein.

• **Lipid and Mineral Bioavailability:** Microbial lipases hydrolyze complex lipids (triglycerides) into free fatty acids, which are more easily utilized for energy by aquatic animals. Furthermore, the process facilitates the chelation of inorganic minerals, transforming them into more bioavailable organic forms, thus improving mineral absorption and utilization (Ramachandran, Bairagi, & Ray, 2005).

• **Reduction of Anti-Nutritional Factors (ANFs):** Microbial enzymes, particularly phytase, effectively degrade ANFs. SSF can reduce phytate content in soybean meal by over 50%, improving the bioavailability of phosphorus and other minerals (Van der Meulen, et al., 2019), mitigating its negative environmental impact (eutrophication) (Ramachandran et al., 2005). The process also degrades other anti-nutrients such as tannins and toxins. Notably, in substrates derived from transgenic crops, the fermentation process has been reported to break down residual transgenic DNA, potentially eliminating transgenic cells and addressing biosafety concerns.

• **Improved Digestibility and Amino Acid Profile:** The enzymatic hydrolysis of complex carbohydrates and proteins increases the digestibility of the final product from approximately 40% to over 60%. Furthermore, microbial synthesis can enhance the levels of essential amino acids, such as lysine, by 15-20% (Adebayo, et al., 2018).

• **Probiotic and Prebiotic Effects:** The process yields a final product rich in beneficial microorganisms (10^8-10^9 CFU/g) and their metabolites, which can function as probiotics and prebiotics, respectively, when included in the feed (Irianto & Austin, 2002).

• **Synthesis of Bioactive and High-Value Compounds:** SSF is a low-cost method for the de novo synthesis of a wide array of beneficial compounds. This includes the generation of essential "alphabetic vitamins" (A, B-complex, C, D, E, K) and potent antioxidants such as ergothioneine (ET) and pyrroloquinoline quinone (PQQ) (Liang, Zhang, & Wu, 2021). Naturally produced intracellular flavonoids like dihydroquercetin (DHQ) further enhance the product's antioxidant capacity. Importantly, SSF can enrich the feed with high-value additives that are typically expensive supplements, such as the omega-3 fatty acid docosahexaenoic acid (DHA) and the carotenoid pigment astaxanthin, which improves flesh coloration and health (Ahmad et al., 2020).

• **Enhancement of Palatability:** The fermentation process leads to the formation of various structurants (phenols, flavonoids, terpenes) and volatile aromatic compounds, which can improve the palatability and attractiveness of the feed, thereby promoting higher feed intake by the target species.

3. Benefits for Tilapia and Vannamei Shrimp

3.1 Growth and Feed Efficiency

Numerous studies have demonstrated that the inclusion of SSF-derived ingredients improves growth and feed utilization. Enhanced digestibility and nutrient availability lead to an increase in the Specific Growth Rate (SGR) by 10-20% and a reduction in the Feed Conversion Ratio (FCR) by 15-25% in both tilapia and shrimp (Az-Zahra, Huda, & Ahmad, 2021). For tilapia, diets incorporating up to 30% FSBM can effectively replace fishmeal without compromising growth, achieving SGRs of 3.5-4% day^{-1} and FCRs below 1.5 (Zhou, Liu, & Mai, 2010). A recent study reported that tilapia fed SSF soybean meal had 12% higher final biomass and 8.5% better growth compared to controls (Li et al., 2024). In L. vannamei, diets containing 20-30% fermented rice bran have been shown to increase weight gain by 15% and survival by 10-20%, particularly in biofloc systems where fermented flocs provide supplemental nutrition (Anusorn & Ryu, 2017). This improved general digestibility translates directly into more efficient muscle deposition of crude protein, crude lipids, and free amino acids, leading to higher biomass gain.

3.2 Health and Immunity

Fermented feeds function as powerful immunonutritional supplements that enhance host health through multiple pathways:

- **Gut Health and Probiotic Action:** The introduction of probiotics modulates the gut microbiota, increasing beneficial bacterial populations (e.g., Lactobacillus) and competitively excluding pathogens (Vine, Leukes, & Kaiser, 2006). Histological analyses confirm these benefits, showing a 20-30% increase in intestinal villi length and reduced gut inflammation (enteritis) due to the degradation of ANFs (Standen et al., 2013).
- **Metabolic and Anti-inflammatory Modulation:** SSF metabolites exert systemic effects on host physiology. Studies have demonstrated a positive anti-inflammatory response in animals fed fermented ingredients, associated with improved lipogenesis and enhanced hepatic antioxidant capacities. This is supported by molecular evidence showing that SSF diets can increase the expression of liver Acetyl-CoA carboxylase alpha mRNA (promoting fatty acid synthesis for energy storage) while reducing lipase mRNA expression. The process also increases plasma levels of antioxidant enzymes such as superoxide dismutase and catalase, while modulating LDL cholesterol and triglyceride levels, indicative of a healthier lipid metabolism (Dawood et al., 2020). In tilapia, SSF-based diets have been shown to upregulate the expression of key immune-related genes, such as Insulin-like Growth Factor 1 (IGF-1) and lysozyme, enhancing resistance to pathogens like Aeromonas hydrophila by 30-50% (Adebayo et al., 2018). For vannamei, including 10-20% fermented soy pulp in diets improves the activity of antioxidant enzymes (SOD, GPx), reduces Vibrio loads in the hepatopancreas, and increases post-challenge survival by up to 25% (Ren et al., 2019). Histological analyses confirm these benefits, showing a 20-30% increase in intestinal villi length and reduced gut inflammation due to the degradation of ANFs that can cause enteritis (Standen et al., 2013).
- **Synthesis of Immunomodulatory and Protective Compounds:** Beyond probiotics, SSF generates a host of bioactive molecules. Neuroprotectors like Nicotinamide Mononucleotide (NMN), alongside antimicrobial peptides and antibodies, are secreted by the fermenting microorganisms. Furthermore, the process yields various organic acids (e.g., ferulic acid) and by-products like ergotamine, which exhibit direct antipathogenic effects against pathogenic bacteria and can contribute to the destruction of certain viruses, acting as both immune system boosters and natural feed preservatives (Ringo, Olsen, & Schillinger, 2018).

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3.3 Environmental and Economic Advantages

SSF technology promotes a circular economy by valorizing agricultural wastes. This reduces the need for fishmeal by 20-50%, alleviating pressure on wild fish stocks (Cao, et al., 2012). The application of SSF to aquaculture sludge, in particular, not only recycles nutrients but also boosts the quality of biofloc in integrated systems, with the microbial community acting

as an environmental improver and bioremediator. In integrated systems like tilapia-shrimp polyculture, fermented feeds can also improve water quality by lowering ammonia concentrations by 20-30%. Economically, the use of locally sourced wastes can lower feed costs by 15-25%, significantly boosting profitability. Collectively, these improvements in animal survival and welfare allow for sustainable crop intensification, maximizing production without compromising environmental or animal health.

4. Challenges in Implementation

Despite its benefits, the widespread adoption of SSF faces several hurdles:

• **Process Optimization and Consistency:** The high variability in the composition of agricultural wastes necessitates strain-specific process optimization. Suboptimal conditions (e.g., pH >7, improper moisture) can reduce fermentation yields by 30-40% and lead to batch-to-batch variability of 10-20% (Pandey, 2003).

• **Scalability and Cost:** Translating lab-scale success to industrial production is challenging due to the risks of contamination and the energy requirements for aeration and sterilization in large-scale systems. Initial capital costs for bioreactors (10,000−50,000) can be prohibitive for small-scale cooperatives without external funding.

• **Safety and Quality Control:** The use of unsterilized wastes and fungal inoculants carries a risk of mycotoxin (e.g., aflatoxin) contamination. Furthermore, regulatory frameworks for the use of probiotics in animal feeds vary by region, potentially creating barriers to market entry.

• **Species-Specific Responses:** The nutritional benefits are not universal across all species. For instance, high inclusion levels (>30%) of fermented products can depress growth in carnivorous species like vannamei shrimp due to imbalanced amino acid profiles, whereas omnivorous tilapia are more tolerant.

• **Regional Limitations:** In developing regions, access to high-quality microbial inoculants, technical expertise, and monitoring tools is often limited, leading to inconsistent product quality.

5. Future Prospects

SSF holds transformative potential for the future of aquafeed. Key areas of development include:

• **Technological Advances:** The use of AI-optimized bioreactors to control fermentation parameters in real-time and the application of genetic engineering (e.g., CRISPR-edited Bacillus for enhanced enzyme yields) could reduce fermentation time by up to 50% and costs by 30%.

• **Novel Substrates and Strains:** Valorizing emerging waste streams like citrus peels and spent mushroom substrate with multi-strain microbial consortia could yield feeds with 25-40% protein and omega-3 enrichment. For shrimp, using chitinolytic strains on shrimp shell waste could produce pre-digested chitin feeds, a natural growth promoter.

• **Health-Focused Innovations:** Developing SSF feeds with targeted immunomodulators (e.g., β-glucans) could reduce antibiotic usage by up to 50%, addressing the critical issue of antimicrobial resistance.

• **Policy and Economic Scaling:** Circular economy models predict that SSF could contribute to a 20-30% gain in global feed sustainability by 2030. Government policies and subsidies supporting waste-to-feed technologies, particularly in Asia and Latin America, are crucial for scaling adoption.

• **Closing Research Gaps:** Further research is needed on the long-term, multi-generational effects of SSF feeds on fish health and genetics. Life-cycle assessments are also required to quantify the full environmental benefits.

6. Conclusion

Pre-digested aquafeeds produced via solid-state fermentation of local agricultural wastes offer a viable and powerful pathway to sustainable tilapia and vannamei shrimp production. This technology simultaneously enhances nutrient valorization, improves animal growth and health, and provides significant environmental and economic benefits. While challenges in scalability, cost, and quality control remain, they are not insurmountable. Targeted innovations in biotechnology, process engineering, and supportive policy-making will be key to unlocking the full potential of SSF. Continued interdisciplinary research and investment promise to establish SSF as a cornerstone of a resilient and circular aquaculture future, fostering global food security.

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Unlocking the Potential of Indonesia's Native Shrimp: A Path to Domestication

Introduction

At present, there is a wide array of shrimp dishes with various flavors that people enjoy, easily accessible in markets. The consumed shrimp these days mostly come from controlled breeding efforts. These shrimps have been bred from wild origin successfully over many years (Liao et al., 2016). The diverse genetic variations in wild shrimp have been adapted to controlled breeding conditions. Domestication involves modifying organisms from their wild origins through selective breeding in controlled environments to acquire traits beneficial to human (Teletchea and Fontaine, 2012).

The primary aims of domestication are for food and ornamental purposes. As a food source, a successful example of domestication is the vannamei shrimp, now dominating the global shrimp cultivation market as a high-protein food sources commodity. Many broodstock providers have successfully become major players in vannamei shrimp breeding, such as American Penaeid Inc. (API), Shrimp Improvement Systems (SIS), Kona Bay Shrimp (Kona Bay), CP Foods (CPF), SyAqua, and Top Aquaculture Technologies, which collectively meet 85% of the world's broodstock production (van der Pijl, 2020). This breeding began in the late '80s and was introduced in the early '90s. However, its farming success commenced in the '70s (Wyban, 2019).

The second domestication goal is for ornamental reasons, such as achieving specific colors. For instance, the ornamental shrimp *Neocaridina davidi* or N. *denticulata*, native to Taiwan, was introduced to the ornamental fish industry in 2003 (Han et al., 2019). The domestication of ornamental shrimp was predominantly carried out by aquarium hobbyists in the preceding decade. This domestication has resulted in various colors such as red, blue, orange, yellow, and green (Suen and Gillett-Kaufman, 2020).

Which species should be domesticated and what are the scenarios? Domestication scenarios can be directed to explore as many advantages within a species, known as intraspecific domestication. This is the goal of selective breeding, as seen in the breeding of Nile tilapia *(Oreochromis niloticus)*, common carp *(Cyprinus carpio)*, Atlantic salmon *(Salmo salar)*, and vannamei shrimp *(Penaeus vannamei)*. Advantages in these species such as growth, feed efficiency, and disease resistance are the main targets. The second scenario involves domestication for commodity diversification. Interspecific domestication is exemplified by diversification within a genus, such as catfish, for instance Clarias gariepinus, *Clarias macrocephalus, Clarias batrachus, and Clarias nieuhofii.* In reality, in aquaculture, only a few species undergo total domestication, reaching the level of genetic selection. Most cultivated species still rely on natural

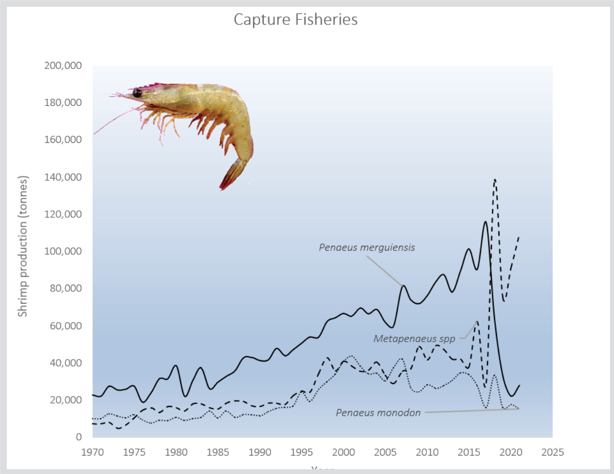

Figure 1 . Shrimp production from capture activity

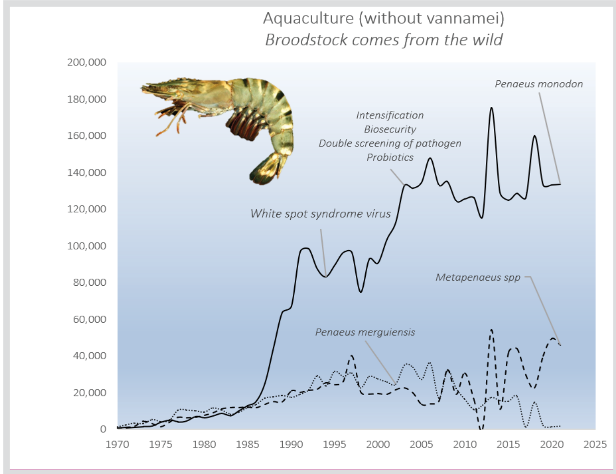

Figure 2. Shrimp production from aquaculture especially P. monodon.

sources (Teletchea and Fontaine, 2012).

The History of Shrimp Domestication

The journey began in the 1930s when Dr. Motosaku Fujinaga (1903–1974), later known as the Father of Japanese Shrimp Aquaculture, successfully bred kuruma shrimp *(Penaeus japonicus)* in 1933. Despite setbacks during World War II, hatchery technology advanced rapidly, and by 1967, shrimp seed production was well established (Fujinaga, 1967).

The next breakthrough came from Taiwan. Dr. I Chiu Liao (1936–present), widely recognized as the Father of Taiwanese Tiger Shrimp Aquaculture, successfully spawned black tiger shrimp *(P. monodon)* in 1969. Tiger shrimp farming peaked in the late 1980s, shaping Asia's aquaculture boom (Liao et al., 2016).

In Indonesia, shrimp domestication efforts were pioneered by Dr. Made L. Nurjana (1950–present). After joining the Brackishwater Aquaculture Center in Jepara in 1976, he achieved successful breeding of P. monodon using unilateral eye ablation in 1978. By the early 1980s, he introduced small-scale hatchery models inspired by Taiwan, laying the foundation for Indonesia's shrimp farming industry (Utama and Haryanto, 2008).

The Role of Domesticated Shrimp to Indonesian Shrimp Production

Indonesia's shrimp story reflects both opportunities and challenges. According to FAO, *P. merguiensis* was historically the main shrimp landed from capture fisheries, increasing from ~20,000 tonnes in 1970 to ~100,000 tonnes in 2015 before declining in 2020.

The introduction of tiger shrimp farming in the mid-1980s transformed production, surging from ~20,000 tonnes in 1985 to ~100,000 tonnes in 1993. However, the emergence of white spot syndrome virus (WSSV) in 1994 limited further expansion, with production peaking around 180,000 tonnes in 2015 (FAO, 2023).

A revolution occurred when P. vannamei was introduced with selective breeding and SPF (specific pathogen-free) broodstock. Vannamei production skyrocketed from ~50,000 tonnes in 2005 to ~750,000 tonnes in 2021, about five times that of black tiger shrimp.

Scientific name	International trade	Domestication status
Penaeus monodon	Black tiger shrimp	Breeding program (BPBAP Jepara) CLASS 5
Penaeus merguiensis	Banana shrimp	Breeding program (BPBAP Jepara) CLASS 5
Penaeus indicus	Indian white shrimp	Breeding program (BPBAP Jepara) CLASS 5
Penaeus semisulcatus	Green tiger shrimp	Spawning from wildstock (BRPBAP Maros); CLASS 3
Penaeus simplex	Aceh Banana Shrimp	Spawning from wildstock (BPBAP Ujung Batee); CLASS 3

Table 1. Domestication status of several indonesian indigenous shrimps

Today, shrimp farming contributes nearly 80% of Indonesia's shrimp production, reflecting a 55-fold increase over the past five decades (FAO, 2023).

Domestication Status of Indonesian Native Shrimp

The key question is: what comes after vannamei? Relying on a single species is risky, hence the need to domesticate native shrimp. As the saying goes, "don't put all your eggs in one basket."

Domestication progresses through stages, from acclimating broodstock in captivity, to closing the life cycle, to selective breeding without reliance on wild stocks. In Indonesia, five species have undergone domestication trials: P. monodon, P. merguiensis, P. indicus, P. semisulcatus, P. simplex (Mangampa et al, 2016), Nur et al, 2022; Sahidhir and Nur, 2016; Wiradana et al, 2020;

Of these, three (*P. monodon, P. merguiensis, P. indicus*) have reached level 5, with selective breeding reported, while *P. semisulcatus* and *P. simplex* still depend on wild broodstock. The first level involves acclimatizing shrimp to the culture environment. Shrimp are introduced into captivity, fed until maturity, and then spawned. The eggs are artificially hatched, and the larvae are successfully reared up to the nursery and grow-out stages. The second level of domestication denotes that part of the life cycle is completed in captivity, but significant challenges persist. The third level indicates that the entire life cycle occurs in captivity, yet wild broodstock is still utilized. The fourth level is attained when there's no need for wild broodstock, though no breeding program is in place. The highest level of domestication is reached when no wild input is required, and a breeding program exists (Teletchea and Fontaine, 2012).

Variables	Values	Unit
Pond area	600	m^2
Shrimp stock	4.600	ind
Tilapia stock (1/46 ratio)	100,0	ind
Shrimp production	59	kg
Tilapia production	10	kg
Average body weight	16,6	g
Shrimp SR	77%	
Shrimp FCR	0,68	
Duration of culture	88	days
Salinity	5-25	ppt

Tabel 2. Penaeus simplex production performance polycultured with tilapia

Case Example: P. simplex

P. simplex, recently described as Aceh's indigenous marine shrimp (Chan et al., 2021), has shown strong promise. The species has been identified across seven regencies in the Aceh

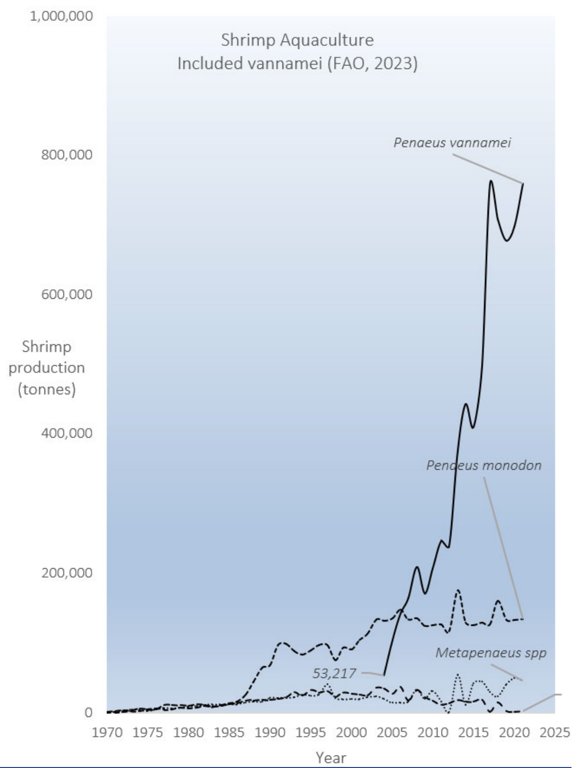

Figure 3. Shrimp production from vannamei farming

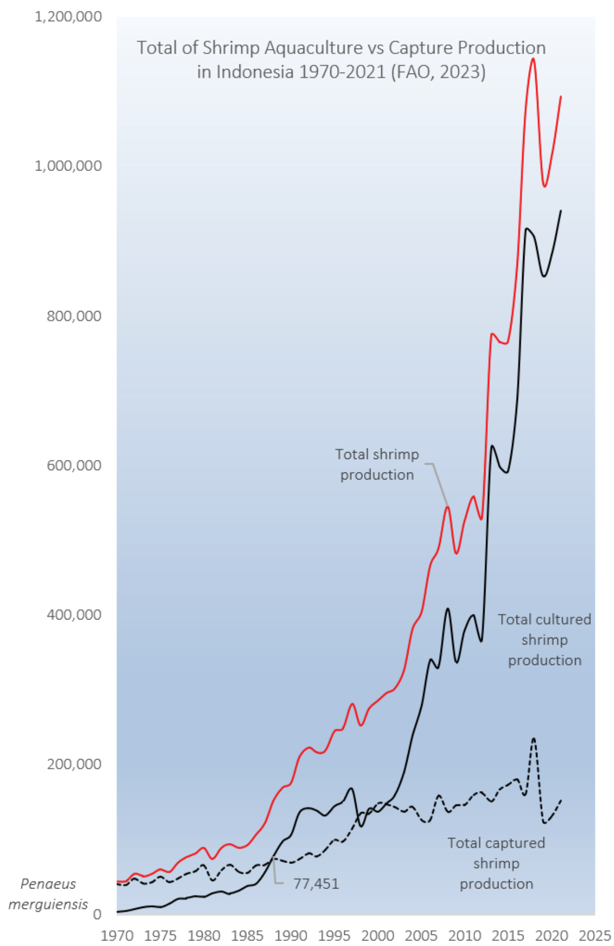

Figure 4. Total shrimp production from captured and cultured sector

Province, tip of Sumatera (BPBAP UB, 2014). P. simplex has demonstrated successful maturity and spawning in captive conditions, producing eggs that hatch into nauplii. The larvae were nourished with a diet comprising *Skeletonema, Chaetoceros, Thalassiosira*, artificial feed, and Artemia nauplii. There was no significant difference in egg production between ablated and non-ablated females with acceptable survival rate. In polyculture trials with tilapia, survival was acceptable under low-input, rain-fed conditions. Though still early, these results suggest potential for scaling up (Sahidhir and Nur, 2016).

In terms of its economic significance, P. simplex has been previously sold in Japan and Europe. The shrimp was marketed at a local price ranging between USD 4.5 to 10.5. Biologically, this species is closely related to *P. monodon* (Chan et al., 2021). From a zootechnical perspective, it has been possible to spawn this shrimp using wild broodstock, but there has no report for second generation production in captivity (Nur et al., 2017). Being native to Indonesia, it is presumed to be environmentally friendly and supportive of local biodiversity. This could potentially grant the local community intellectual rights concerning geographical indicators. In terms of regulatory aspects, both the Indonesian government and the international community support the farming of local species.

Economically, *P. simplex* has been marketed in Japan and Europe at USD 4.5–10.5/kg. Biologically, it is closely related to *P. monodon*. From a sustainability standpoint, farming *P. simplex* could reduce dependence on imports while promoting local biodiversity and geographic branding.

Yet major gaps remain : reproductive biology in the wild, nutritional requirements, hatchery performance, and grow-out performance under controlled systems are still poorly documented. Selective breeding programs for this species have not begun.

Beyond Competition with Vannamei

Domestication of Indonesia's native shrimp is not about replacing or competing head-to-head with *P. vannamei*. Instead, it is about diversification and resilience. Vannamei will remain the global commodity shrimp, while native species can occupy niche and premium markets, reflecting Indonesia's biodiversity and cultural identity.

This strategy mirrors global aquaculture: salmon dominates the market, but trout, char, and seabass thrive in specialty segments. For Indonesia, native shrimp like *P. simplex* could serve similar roles, creating new opportunities without undermining existing strengths.

The future of Indonesian aquaculture will depend not only on sustaining vannamei but also on broadening its species base. Domestication of native shrimp represents an opportunity to reduce systemic risk, enhance sustainability, and showcase Indonesia's unique biodiversity to the world.

For *P. simplex* and others, much work remains, from reproductive biology to selective breeding, but early progress is encouraging. With coordinated efforts, Indonesia's native shrimp could become the next pillar of sustainable aquaculture.

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Aquaculture

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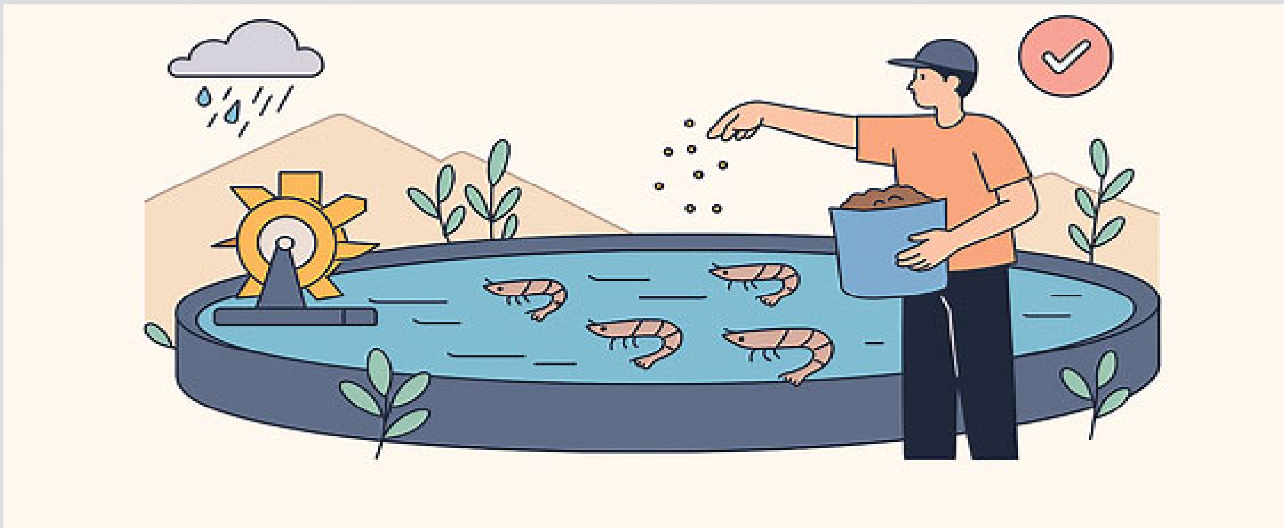
Health and feed management in the shrimp culture system



Introduction

Global aquaculture is now the dominant source of aquatic animals. In 2022, total fisheries and aquaculture output hit a record 223.2 million tons, and—crucially—for the first time aquaculture out produced capture fisheries for aquatic animals: 94.4 million tons of farmed animals versus 91.0 million tons from capture. Asia accounts for ~70% of aquatic-animal output, and "fed aquaculture" (species that require external feed, like shrimp) made up ~73% of farmed animals, underscoring how central feed is to the sector's footprint and profitability (FAO Report, 2024).

Within that picture, shrimp is a flagship commodity—large in volume and hyper-sensitive to costs, biosecurity, and market swings. After a supply dip in 2023, analysts expect a renewed production push, with industry commentary pointing to a 2025 global shrimp harvest approaching ~6 million tons as Ecuador and parts of Asia expand capacity; at the same time, recent price softness has squeezed margins and made efficiency paramount. The net effect is a sector where performance hinges on managing grams of feed, percentage-points of survival, and points of feed conversion ratio (FCR) (FAO Report, 2024).

Shrimp is one of the most delicious seafood, and well accepted all over the world. The domestication of various species, like Penaeus mondon, P. vannamei, P. chinesensis, and P. japonicas and P. indicus made the shrimp farming more approachable. The most popular and widely cultured species at the moment is P. vannamei, which is commonly known as white shrimp, due to its wide range of salinity tolerance (4 to 40 ppt), tolerant to various pathogens compared to other species, and its habitat column feeder (Chong-Robles et al., 2013).

The feeding habit of Vannamei is quite variable. From various studies it has been seen that the growth rate and survival rate of Vannemi is almost same whether it is fed on crude protein 20 to 40% (Sores et al., 2021). The feed cost considered as the major portion 60-70% of the total production cost, and shrimp is able to consume only up to 60% of the provided feed. The remaining 40% gone as waste and accumulates at the pond bottom. Feed trays are used to measure the feeding rate in the shrimp ponds.

Feeding management in aquaculture, especially in shrimp farming, is one of the most critical challenges faced by farmers and technicians. Shrimp, unlike some other cultured species, do not consume all the feed provided to them. Studies and practical observations indicate that shrimp consume only about 60% of the feed supplied in a pond. This creates a significant concern for aquaculture operations because the remaining uneaten feed does not just represent a financial loss, but also poses a serious threat to the pond environment.

When excess feed accumulates at the bottom of the pond, it undergoes decomposition, which results in the release of harmful gases such as ammonia, nitrite, and hydrogen sulfide. These toxic substances can deteriorate the water quality, reduce oxygen levels, and stress the shrimp population. Prolonged exposure to such poor conditions often leads to disease outbreaks, reduced growth rates, and in severe cases, large-scale mortality. Thus, improper feeding management is not just a matter of feed wastage but directly impacts productivity and profitability (Dung et al., 2025).

For this reason, feeding management requires a skilled and attentive approach. A technician must carefully monitor shrimp behavior, feeding trays, and pond conditions to determine the right amount of feed and timing. Shrimp tend to eat more actively at certain times of the day, and this must be factored into the feeding schedule. Using feed trays or demand feeders can help monitor actual consumption and minimize waste. Furthermore, high-quality, water-stable feed that sinks gradually can reduce losses, as shrimp are bottom feeders and require time to locate food.

Ultimately, efficient feeding management is about balancing shrimp health, feed utilization, and environmental sustainability. Technicians play a key role in optimizing feeding strategies, ensuring that shrimp receive enough nutrition for healthy growth while minimizing wastage and maintaining water quality. A well-managed feeding system not only improves productivity but also reduces costs and environmental impact, making aquaculture more sustainable.

Why feed management is pivotal ?

Feed is typically the largest single operating cost in shrimp farming—often the majority of cash costs—so even small efficiency gains matter. Typical FCRs for penaeid shrimp span ~1.2–2.0 under commercial conditions; every 0.1 change in FCR materially shifts profit and waste loads. Overfeeding doesn't just burn money: uneaten pellets leach nutrients, depress water quality, and set up downstream health problems. Studies and farm trials show that higher-frequency, well-distributed meals via automated or demand-based feeding can improve growth, lower FCR, and reduce waste compared with coarse, manual schedules. Newer work in intensive systems has found 6–8 micro-meals/day via automatic feeders outperforming manual routines on growth, FCR and profitability; acoustic/feedback-controlled feeding has also delivered lower FCRs and larger shrimp in trials. Extruded shrimp feeds are another lever, often improving feed conversion versus conventional pellets due to better water stability and nutrient availability. Practically, trays remain useful for calibration, but farms increasingly pair them with sensors/cameras to titrate rations in real time.

Why health management is non-negotiable ?

Shrimp lack adaptive immunity like vertebrates, so prevention beats treatment. The pathogen landscape is dynamic: white spot syndrome virus (WSSV) remains ever-present; acute hepatopancreatic necrosis disease (AHPND/EMS) and Enterocytozoon hepatopenaei (EHP) continue to challenge intensive sites, contributing to slow growth, white feces syndrome, and erratic harvests. Best practice emphasizes specific-pathogen-free (SPF) broodstock, tight biosecurity (water intake treatment, bird/crab exclusion, equipment control), regular PCR screening, and movement controls aligned to WOAH (OIE) standards (FAO Reports 2024). On antimicrobials, the direction of travel is clear: regulators and markets are narrowing the space for antibiotic use, and FAO/WOAH now promote progressive, farm-level monitoring of antimicrobial use (AMU), residue surveillance, and non-antibiotic controls. Recent guidance codifies how countries and farms should track AMU and strengthen biosecurity; at the border, shipments with residues face rejection, keeping pressure on the supply chain to prevent

Mean Body weight (g)	Biomass Percentage	Feeding Frequency	Feed Type and diameter (mm)	Length (mm)
PL 10- Juvenile	Blind feeding	3	crumble	0.4-0.8
1.0 to 2.5	Blind feeding	3	crumble	0.8-1.4
2.5 to 8	17-20	4	Pellet 1.5	1.5-2.6
8-18	5-7	4	Pellet 1.8	2.0-3.0
18-25	4-5	4	Pellet 2	2.0-3.5
>25	3-4	4	Pellet 2.2	2.0-4.0

Table1: Recommended feed size and type of feed for Vannamei shrimp

misuse. In short: robust health management lowers mortality and stabilizes FCR—two outsized profit drivers.

Why water quality management is the system throttle ?

Dissolved oxygen (DO) is the most limit-setting parameter in intensive ponds. A practical rule is to keep DO at or above ~5 mg/L for shrimp; dips below this band reduce feeding, stunt growth, and can trigger mortality cascades. Continuous aeration and night-time DO monitoring are standard in high-density ponds. Precision-aeration and forecasting (e.g., data-driven DO prediction) let farms pre-empt dawn troughs and feed accordingly.

Nitrogen control is next. Unionized ammonia (NH_3)—the toxic fraction of total ammonia nitrogen—rises sharply with higher pH and temperature; that's why a hot, sunny afternoon after heavy feeding is risky. Managing loading (feed input), maintaining alkalinity for nitrification, and avoiding pH spikes reduce NH_3 risk. Nitrite (NO_2-N) is also hazardous; a common practice is to aim for near-zero NO_2-N and, when spikes occur, use chloride additions (e.g., salt) to competitively inhibit nitrite uptake across the gills—a 10:1 chloride-to-nitrite ratio is widely cited in pond fish and carries over operationally to shrimp. Regular testing of TAN, nitrite, pH, alkalinity, and morning DO, plus responsive aeration/water exchange or biofloc adjustments, are the core toolkit.

Biofloc systems (properly managed) can turn waste into microbial protein, improving water quality and sometimes reducing FCR by letting shrimp graze on biofloc. They're not a silver bullet—floc density, carbon dosing, and aeration demand must be balanced—but used well they tighten nutrient loops and reduce discharge.

The three levers reinforce—or undermine—each other

These pillars are intertwined. Feed sets the biochemical load on the pond; water quality determines whether shrimp will eat that feed and convert it; health status governs how much of that conversion shows up as saleable biomass. Overfeeding → ammonia/nitrite spikes → DO stress → reduced feeding/weak immunity → opportunistic pathogens (e.g., Vibrio spp.) → higher FCR and mortality. Conversely, a farm that meters feed to appetite (automation + tray/video feedback), keeps DO comfortably high, and enforces biosecurity/diagnostics, generally sees tighter FCRs, fewer crashes, and more predictable harvest windows.

Precision tools are accelerating this integration. Camera and computer-vision systems can read feeding plates and shrimp activity; automatic feeders can micro-dose rations throughout the day; decision-support models can forecast DO and flag anomalies so managers throttle feed and aeration proactively. As capital costs fall, these technologies shift from "nice-to-have" to core risk control—particularly in regions facing chronic price pressure.

A critical take: where to focus ?

Feed discipline, not just cheaper feed. FCR is a composite outcome of rationing, pellet quality, distribution, and shrimp health. Extruded feeds and higher-frequency micro-meals often pay for themselves via lower FCR and cleaner bottoms. Pair trays with cameras or acoustic feedback to stop when appetite drops, and re-budget feed daily from growth checks rather than static tables.

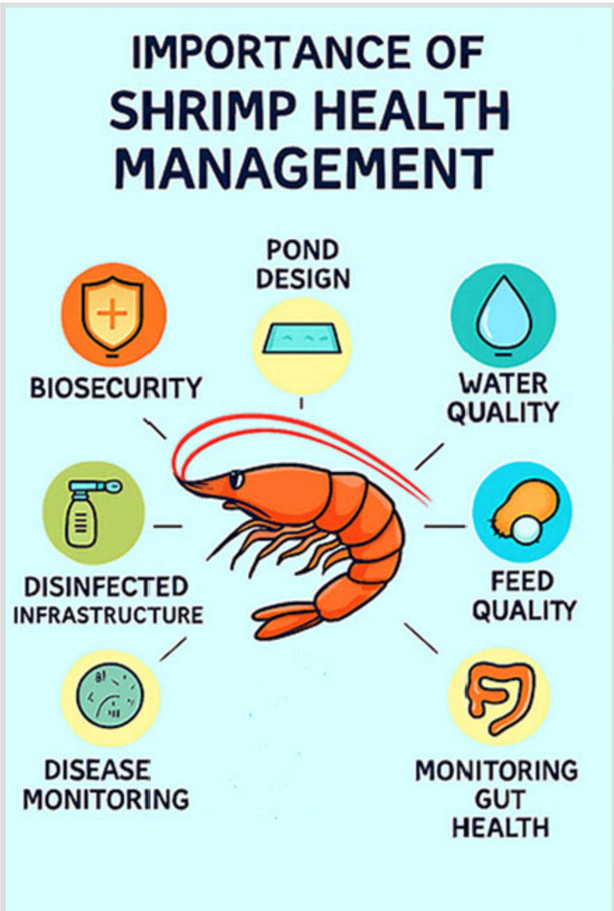
Biosecurity first, antibiotics last. SPF seed, pathogen-aware sourcing, water treatment, and routine PCR shrink outbreak probability. Align farm SOPs with FAO/WOAH AMU monitoring guidance; use probiotics, immunostimulants, and management fixes before reaching for drugs, and document any veterinary use rigorously.

Engineer the pond for oxygen and nitrification. Design and operate aeration to keep DO ≥ ~5 mg/L with headroom for hot, cloudy spells; watch the TAN–NO_2–NO_3 arc daily, and manage pH/alkalinity so nitrifiers thrive. Prepare salt for acute nitrite events and avoid big afternoon pH spikes that convert NH_4^+ to NH_3.

In a market where shrimp prices can be volatile and input costs remain stubbornly high, farms that treat feed, health, and water as one system are the ones that win: fewer surprises, steadier survival, lower FCR, and better margins—all while shrinking waste and environmental load. That's the aquaculture flywheel the sector now needs to scale.

Importance of Shrimp Health Management

Shrimp farming is one of the fastest-growing segments of global aquaculture, but it is also one of the most vulnerable. Unlike finfish, shrimp lack a strong adaptive immune system, which means they cannot "remember" pathogens and mount targeted defenses. Consequently, they are highly susceptible to bacterial, viral, and parasitic diseases such as white spot syndrome virus (WSSV), acute hepatopancreatic necrosis



disease (AHPND/EMS), and Enterocytozoon hepatopenaei (EHP). Outbreaks can wipe out entire crops within days, leading to catastrophic economic losses and reduced farmer confidence.

Effective shrimp health management ensures higher survival, better growth rates, and lower feed conversion ratios (FCR), all of which translate into improved profitability and sustainability. Moreover, robust health management helps farmers comply with international food safety standards, particularly concerning antimicrobial resistance and residue control, which are closely monitored in export markets.

Key Methods of Shrimp Health Management

1. Seed Quality and Biosecurity

o Stocking disease-free shrimp seed is the first step. Hatcheries producing Specific Pathogen Free (SPF) or Specific Pathogen Resistant (SPR) post-larvae are preferred.

o Biosecurity protocols include filtering and disinfecting intake water, preventing the entry of birds, crabs, or other carriers, restricting visitor access, and disinfecting equipment.

2. Water Quality Management

o Maintaining optimal levels of dissolved oxygen (≥ 5 mg/L), temperature (28–32°C for many penaeid species), pH (7.5–8.5), and low levels of ammonia and nitrite is critical for shrimp immunity. Poor water conditions stress shrimp and make them more vulnerable to opportunistic pathogens such as Vibrio spp.

3.Nutrition and Feed Management

o Balanced diets with adequate protein, lipids, and micronutrients strengthen shrimp health.

o Feed additives such as probiotics, prebiotics, immunostimulants, and vitamins (C and E) are often used to improve gut health and resistance to stress.

o Preventing overfeeding reduces organic waste accumulation, thereby lowering the risk of harmful microbial blooms.

4. Regular Monitoring and Diagnostics

o Routine pond-side checks for shrimp behavior, feeding activity, and water quality parameters are essential.

o Laboratory-based PCR screening and histopathology allow for early disease detection.

o Critical thresholds, such as ammonia < 0.1 mg/L (unionized), nitrite < 1 mg/L, and alkalinity 100–150 mg/L, should guide corrective actions.

5. Disease Prevention Strategies

o Use of probiotics in pond water to maintain a healthy microbial balance.

o Application of biofloc technology to reduce pathogen load and improve natural feed availability.

o Vaccination is still under research for shrimp, but immune-boosting approaches like RNA interference (RNAi) and phage therapy show promise.

6. Responsible Use of Antimicrobials

o Antibiotics should be used only under veterinary guidance. Misuse leads to resistant bacteria and market rejection due to residues. International standards (FAO/WOAH) stress monitoring antimicrobial use (AMU) and adopting non-antibiotic alternatives.

Critical Parameters in Shrimp Health Management

• Seed health: SPF/SPR quality, disease-free certification.

• Biosecurity: Water disinfection, exclusion of carriers, staff hygiene.

• Water quality: DO ≥ 5 mg/L, ammonia < 0.1 mg/L (NH_3), nitrite < 1 mg/L, salinity 10–30 ppt (species-specific).

• Nutrition: Balanced feed, FCR ≤ 1.5–1.8, supplements for immunity.

• Surveillance: Regular PCR diagnostics, mortality/growth tracking.

• Antimicrobial stewardship: Minimize antibiotics, use probiotics and immunostimulants.

Critical Analysis of Feeding Tray Management in Shrimp Farming

Feeding management is one of the most critical aspects of commercial shrimp aquaculture. The cost of feed accounts for more than 50–60% of total production expenses, and improper feeding practices can not only inflate costs but also degrade water quality, elevate disease risks, and ultimately reduce farm profitability. Feeding trays have emerged as a valuable tool in optimizing feed usage, monitoring shrimp behavior, and estimating pond biomass. However, their use requires careful design, disciplined observation, and skilled interpretation. This discussion critically analyzes the role of feeding trays, walkway structures, biomass estimation, scoring methods, and feeding cycles in shrimp farming, while also evaluating their practical limitations and implications.

1. Feeding Trays and Walkway Structures

Feeding trays are typically installed along walkways extending at least two meters into the pond from the dyke, with the trays positioned 30–50 cm above the pond bottom. This design ensures that the trays are accessible for observation and stable enough for technicians to work on safely. A stable walkway is not merely a structural requirement; it represents the interface between human monitoring and shrimp response. Without stability and accessibility, feeding trays lose their intended value, as technicians may fail to conduct consistent monitoring.

The allocation of trays is scaled to pond size: four trays for a 0.5-hectare pond, 6–8 trays for a 1-hectare pond, and 8–10 trays for ponds larger than two hectares. While this proportional guideline is practical, it assumes homogeneity in pond dynamics. In reality, water circulation, aeration patterns, and micro-ecological variations within ponds can make feed consumption highly uneven. Thus, a rigid "per hectare" rule may not fully capture the complexity of pond ecosystems. A more critical approach would consider not just pond area but also hydrodynamics, aeration distribution, and shrimp congregation zones in determining tray placement. Over-reliance on fixed numerical rules risks overlooking these environmental factors.

2. Biomass Estimation and Its Challenges

Accurate feed calculation depends on reliable estimates of shrimp biomass. The recommended method combines shrimp weight sampling (via cast net), estimated survival rate, and stocking density. However, these factors are notoriously difficult to measure with precision. Stocking densities may vary significantly: poor transport or acclimation may reduce survival to 80% of purchased post-larvae, while additional "free" larvae may raise densities beyond 120%. Such inconsistencies introduce substantial uncertainty into biomass calculations.

The reliance on "estimated survival rates" from reference tables is particularly problematic. These values often fail under real-world farm conditions, where disease outbreaks, cannibalism, or environmental stressors can cause unpredictable mortality. A more reliable approach is to calculate biomass using the three-day running average of feed consumption. By smoothing daily fluctuations, this method provides a more stable representation of shrimp demand and pond carrying capacity. Skilled technicians, by integrating these data with field observations, can achieve biomass estimates within ±10% accuracy. This is a considerable advantage, as accurate biomass estimation directly influences feed conversion ratio (FCR), harvest planning, and input cost control.

Yet, this approach is not without limitations. It assumes that shrimp consume feed consistently relative to their biomass, but feeding behavior can vary with stress, dissolved oxygen fluctuations, molting cycles, and subtle environmental changes. Therefore, while feed consumption is a useful proxy for biomass, it cannot be treated as an absolute measure. Critical interpretation remains essential.

3. Feeding Tray Observation and Adjustment

One of the strongest arguments in favor of feeding trays is their ability to provide real-time feedback on feed consumption. Feed should be checked after each application or at least daily, and adjustments made accordingly. The suggested adjustment ranges are a 5% increase in feeding if trays are consistently empty and a 10% decrease if excess feed is left behind. This dynamic adjustment mechanism helps maintain growth while preventing wastage and deterioration of water quality.

However, the system assumes technicians are both diligent and skilled in observation. In practice, the accuracy of tray-based adjustments can vary widely between farms depending on staff training, consistency of monitoring, and interpretation bias. For example, distinguishing between "small amounts of feed left" versus "large amounts" can be subjective, particularly under poor visibility conditions. Moreover, shrimp may occasionally ignore trays due to molting or environmental disturbances, leading to misleading signals about feed demand. Relying solely on tray results without contextual analysis may thus cause underfeeding, slowing growth rates, or overfeeding, leading to water pollution.

4. Tray Scoring System: A Structured but Imperfect Tool

The allocation of scores (0 for no feed left, 1 for little feed left, 2 for much feed left) provides a structured framework for feed adjustment. A majority-based rule, where at least 75% of trays must confirm a trend before adjustment, is logical in reducing the risk of overreaction to anomalies in individual trays.

For instance:

• Scores such as 0000 or 0001 suggest full consumption, warranting a 5% increase.

• Scores like 0011 or 1111 indicate satisfactory feeding levels, requiring no change.

• Scores such as 1222 or 2222 imply overfeeding, prompting a 10% reduction.

This method encourages cautious and incremental changes rather than abrupt shifts. Nevertheless, it remains reactive rather than predictive. It tells us what has already happened, not what will happen. For example, shrimp in pre-molt stages often reduce feed intake temporarily. If feeding is reduced aggressively based on tray scores alone, post-molt growth may be compromised. A critical improvement would be to integrate tray scores with predictive data such as shrimp growth curves, environmental monitoring (temperature, dissolved oxygen), and historical consumption trends.

5. Feeding Cycle and Its Critical Stages

Shrimp feeding demand follows a predictable cycle, with feed requirements being modest in the first 30 days and intensifying in the latter half of the grow-out period. During the initial month, when shrimp are small, blind feeding is recommended. This approach is justified, as the total feed input is minimal and the cost of potential wastage is low compared to the risk of underfeeding juvenile shrimp. However, beyond 30 days, precision feeding becomes increasingly critical.

The last two months of production consume the bulk of the feed—often over 60% of total inputs. At this stage, overfeeding has catastrophic implications: it not only wastes expensive feed but also leads to excess organic load, ammonia buildup, oxygen depletion, and heightened disease risks. Conversely, underfeeding during this stage may result in poor growth, smaller harvest size, and suboptimal market value. The margin for error becomes extremely narrow, emphasizing the need for precise observation, timely adjustment, and data-driven decision-making.

6. Strengths, Limitations, and Way Forward

The feeding tray system represents a practical, low-cost, and widely accessible tool for shrimp farmers. Its strengths include:

• Real-time feedback on shrimp feeding behavior.

• Support for biomass estimation and survival rate calculations.

• Flexibility to adjust feed quantities daily.

• Integration with harvest planning (biomass estimation informs ice and transport requirements).

Yet, several limitations undermine its reliability:

1. Subjectivity of observation – tray scoring depends heavily on technician judgment.

2. Lagging indicator – tray results show past feeding but do not anticipate future shifts.

3. Sensitivity to external factors – molting cycles, stress, and water quality issues may distort feeding signals.

4. Overemphasis on uniform rules – ignoring pond-specific hydrodynamics can reduce accuracy.

Future improvements should focus on integrating feeding tray observations with technology-driven systems such as automatic feeders, underwater cameras, and AI-based consumption analysis. Digital tools could reduce subjectivity, predict feeding behavior based on environmental data, and provide a more proactive feeding strategy. Training farm technicians to critically interpret tray results rather than blindly following feeding tables is equally vital.

Conclusion

Shrimp health management is the foundation of successful aquaculture. By focusing on seed quality, biosecurity, water quality, nutrition, and responsible disease prevention, farmers can minimize mortality, stabilize production, and ensure compliance with international trade standards. Given the sector's sensitivity to disease shocks, health management is not optional—it is the decisive factor in whether shrimp farming remains profitable and sustainable. Feeding trays, when used effectively, are powerful tools for feed optimization, biomass estimation, and water quality management in shrimp aquaculture. However, they are not foolproof. Their effectiveness depends on careful placement, disciplined monitoring, skilled interpretation, and integration with broader farm management practices. The critical challenge is balancing feed input with shrimp growth while minimizing waste and environmental impacts. Over-reliance on tray scores or rigid tables can be misleading; instead, a data-driven, adaptive approach that blends traditional tools with modern monitoring technologies offers the most promising pathway. Ultimately, successful feeding management lies not in the trays themselves, but in the critical thinking and adaptive judgment of the farm technicians who use them.

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Aquaculture

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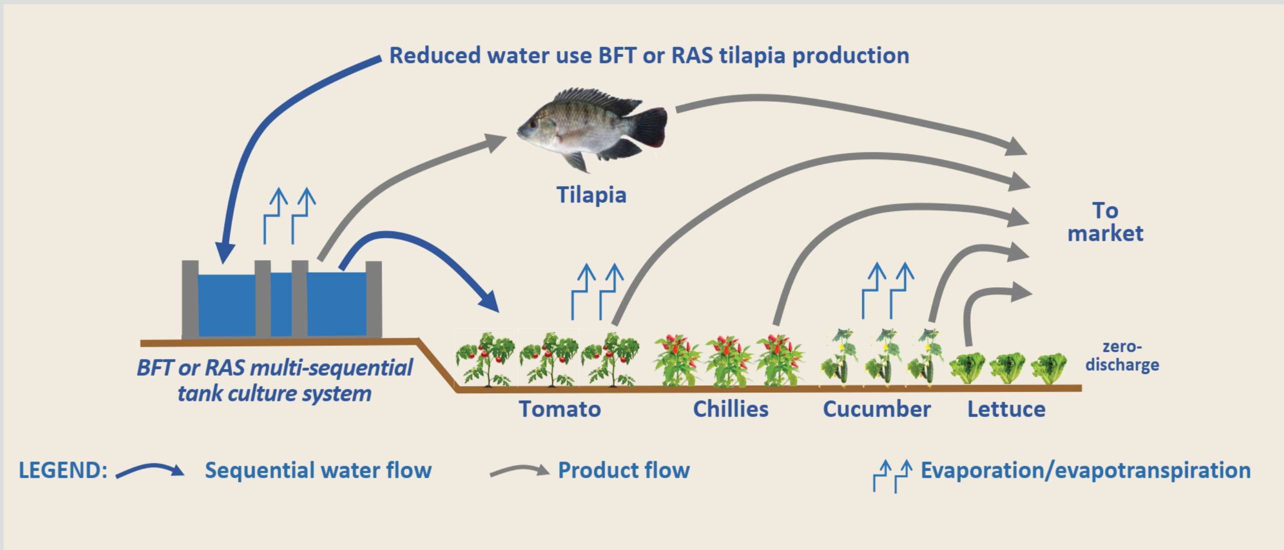
The integration of fish farming into crop irrigation systems for improved water productivity and food security



Introduction

In the current context of resource scarcity, global climate change, environmental degradation, and increasing food demand, the implementation of Integrated Agriculture-Aquaculture Systems (IAAS) to enhance nutrient circularity and food security represents a promising strategy to support sustainable, restorative, and regenerative agriculture.

According to the Food and Agriculture Organization (FAO, 2024) future fish supply growth will originate almost exclusively from aquaculture rather than capture fisheries which has seen a decline since 1996. Farmed aquatic animal production is forecasted to reach 110 million tonnes by 2032 from 94 million tonnes in 2022. Annual average growth in farmed aquatic animal products will fall from 4% per annum observed between 2012-2022 to just 1.6% over the 2022-2032 period attributed to reduced availability of water (both quality and quantity) and suitable aquaculture sites; increasing impact of aquatic animal diseases in intensive aquaculture; and reduced productivity gains under the assumption of a wider adoption of - and enforcement of environmental regulations (FAO, 2024).

Viewed under a broader lens however humanity will be confronted by three impending food security challenges in our efforts to furnish adequate food supplies for a growing global population under climate change uncertainties each of which are briefly considered below:

1) The growing global fish Supply-Demand gap (S-D gap)

Rather than a local phenomenon, global trends point to an acceleration in the decline of the marine catch where most marine capture fisheries stocks are anticipated to collapse before or around 2050 (Worm, et al., 2016). The factors most responsible for the decline of marine capture fisheries are well documented and include, 1) overfishing, 2) ocean acidification, 3) environmental variability and climate change and 4) habitat destruction ((Pontecorvo and Schrank, 2012; Pauly and Zelle, 2016; Edgar et al., 2024; Froese and Pauly, 2024).

Aquaculture already accounts for more than 51% of all aquatic animals consumed by the world in the year 2022 according to the FAO (FAO, 2024). Global aquaculture production in 2022 was computed at 11.81kg/capita [94.4m tonnes of aquatic animals produced and a global population of 7.99 billion] (FAO, 2024; UN, 2025). Future seafood imports should be viewed as a key national economic and food supply vulnerability given less than desirable levels of seafood self-sufficiency for many nations. Future seafood imports should be viewed as a key national economic and food supply vulnerability for nations producing less than the global average of 11.81kg/capita supply level of farmed aquatic animals in the year 2022 in the light of the

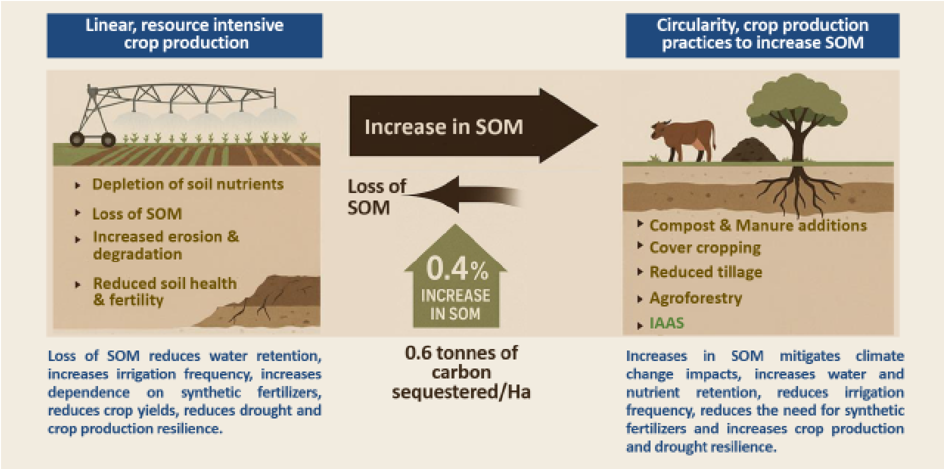


Figure 1: IAAS as a pathway to enhance water productivity and nutrient circularity in transitioned crop irrigation farming systems for improved food security and food production resilience

anticipated impending collapse of global fisheries by or before 2050 (Worm, et al., 2016).

2) Water scarcity amplified by climate change adds to food security risks

Water security for crop irrigation is counted as another vulnerability requiring greater efforts to maximize water productivity in agricultural systems dependent on irrigation under greater levels of water scarcity impacted by climate change (English, 2012).

Greatly improved water productivity in crop agricultural systems will be needed to meet growing global food demands as we approach the year 2050 requiring a multi-pronged approach (English, 2012) to maximize water use productivity. Apart from improved irrigation methods, such as the deployment of drip irrigation and the use of centre pivots along with deficit irrigation, increased soil water retention plays an important role in minimizing the frequency for crop irrigation, and reducing consumptive water use. The United States National Resource Défense Council estimates that a 1% increase in Soil Organic Matter, or SOM (an indicator of soil health) increases soil water storage potential by more than 187,000 litres per hectare (Bryant, 2015).

3) Future food security hinges on embracing sustainable agriculture practices to enhance soil heath and promote food production resilience.

Linear, resource-intensive irrigated crop agriculture can deplete soil nutrients, reduce soil organic matter content, and increase erosion and degradation as well as impact long-term soil health and fertility (Okole et al., 2022). The continual use of chemical fertilizers in the absence of soil amendments eventually depletes Soil Organic Matter (SOM) leading to negative impacts including soil structural changes, reduced microbial activity, reduced soil carbon storage, diminished retention of water and nutrients, leading to decreased crop yields and increased reliance on synthetic fertilizers while reducing overall agroecosystem health (Doran, 2002; Du Preez et al., 2011; Materechera, 2014; Okole et al., 2022; Derpsch et al, 2024).

A meta-analysis of published research studies on SOM and its indicator elements Carbon and Nitrogen for the southern African region observed that compared to adjacent uncultivated fields, crop production leads to an average 46% decline in SOM levels (Swanepoel et al., 2016). Emphasis on the adoption of a circular economy in agricultural systems via increased usage of animal and green manures is being promoted by the EU (EU Commission, 2023), globally by the United Nations (UN, 2020)

Figure 2: Large-scale BFT tilapia aquaculture at Chambo Fisheries, Malawi using 766m3 tanks capable of producing 100 tonnes of tilapia with a consumptive water use of 150L/kg of fish.

Figure 3: BFT R-ended grow-out tank field at Chambo Fisheries, one of the world's largest BFT tilapia fish farms in Malawi with a production capacity of 800 tonnes per annum.

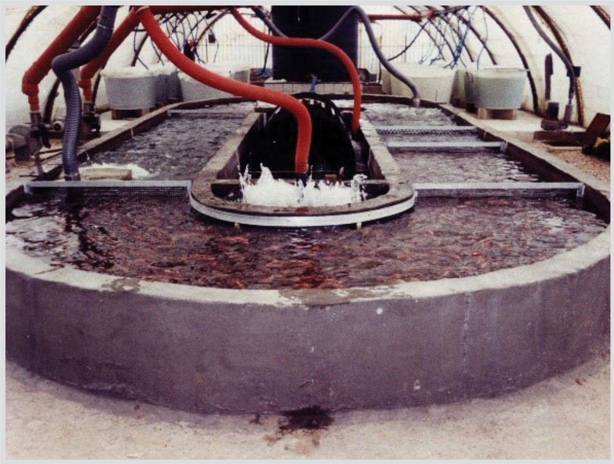


Figure 4: A 10-tonne red hybrid tilapia low pumping head-loss (<100mm), low-energy, all air operated RAS in Lebanon operated at around 368m3 of water use per tonne of fish produced.

Figure 5: A 50-tonne low pumping head-loss (<100mm), low-energy input, all air operated, marine RAS in Tartous, Syria producing Mediterranean Sea bream (Sparus aurata).

and in South Africa (Okole et al., 2022) to reduce Green House Gas (GHG) emissions and bring greater levels of sustainability and food security resilience into farmed food production systems.

Restoring Soil Organic Carbon (SOC) which averages 58% of SOM (USDA, 2022) into soils via the addition of carbonaceous material (viz. livestock manure, green manure, and solid wastes from fish culture etc.) is a key contributor to the global carbon cycle and climate regulation (Beillouin et al., 2023) through the carbon sink in soils. For every 0.4% increase in SOM 0.6 tonnes of carbon per hectare could be sequestered to soils (Minasny et al., 2017; Lal, 2004). By increasing SOM through sustainable practices including agroforestry, compost and livestock and fish manure additions, cover cropping, and reduced tillage, more carbon can be sequestered into the soil to help mitigate climate change impacts.

IAAS presents a triple win strategy when leveraging the synergies between agriculture and aquaculture

Water re-use and nutrient circularity form the cornerstones of integrated aquatic production systems developed into existing crop irrigation systems, also called, Integrated Agriculture-Aquaculture Systems (IAAS). The practice of IAAS has existed for millennia in a variety of regions, such as Egypt, Vietnam, China, and Hawai'I (Costa-Pierce, 1987; Abdul-Rahman et al., 2011; Kaleem and Bio Singou Sabi, 2020; Pueppke et al., 2020). However, the separation and specialization of agriculture and aquaculture systems, facilitated by fertilizers and mechanization, has ingrained economic and infrastructural challenges impeding the rapid transition to commercial-scale IAAS today (Pueppke et al., 2020). IAAS solves three challenges simultaneously:

1) IAAS solves the dilemma of how to increase farmed aquatic animal production sustainably, adding to the national seafood security basket, a national priority in many nations today, in view of declining marine capture fisheries where by around 2050 (Worm, et al., 2016) most marine capture fisheries stocks are anticipated to collapse. National aquaculture development programs in China, India, Egypt and Nigeria (World Bank Projects, 2025) have shown to demonstrably off-set declines in the national wild catch boosting food security, economic development, and sustainable resource management (Naylor et al., 2000).

2) In essence then using the same water for fish farming first enables the sequential re-use of the discharge water for irrigated crops while adding nutrients to the irrigated water supply enabling either no need, or the reduced need, for additive fertilizer usage for crop production (Farrant et al., 2021; Liu et al., 2022) with cost sparing benefits and improved soil health due to the addition of carbon thereby improving agricultural sustainability (Bryant, 2015; Lal, 2004).

3) The problem of emissions from fed aquaculture operations is largely solved when balancing discharge nutrients for crop irrigation within a IAAS overcoming one of the biggest stumbling blocks to achieving sustainable aquaculture production notably the generation of waste water discharge which pollutes waterways resulting in the eutrophication of recipient water bodies (Ahmed et al., 2019).

The appeal of IAAS is that it increases yields using the synergies between agriculture and aquaculture systems to

Culture environment	Solid wastes, Kg/t	Nitrogen N, Kg/t	Phosphorus P, Kg/t	Feed Conversion Ratio, FCR	Ref.
Cage culture, 18% feed losses	1041.6	45.0	14.3	1.60	Neto and Ostrensky (2013)
RAS*1 5% feed losses/ inefficiencies	470.8	38.9	10.7	1.33	Kourie (unpublished)
BFT*2 20% of DE*3 derived via floc grazing	289.7	7.3	6.8	1.09	Kourie(2017d)

Notes: *1 RAS, Recirculation Aquaculture System
*2 BFT, Biofloc Technology
*3 DE, Digestible Energy

Table 1: Solid wastes, nitrogen (N) and phosphorus (P) waste discharge per tonne of tilapia production in cage culture, RAS and BFT aquaculture systems in units of kilograms of waste per tonne of fish produced

improve the efficiency with which energy – and nutrient inputs are converted to food (Ahmed et al., 2019; Pueppke et al., 2020) without the negative trade-offs of nutrient pollution from the waste stream from aquaculture operations (Farrant et al., 2021). Contrary to popular thinking, fish farming "borrows water" and is considered a water sparing farming activity particularly Recirculation Aquaculture Systems (RAS) (Brown et al., 2024) [Fig's. 4 and 5] and Biofloc Technology (BFT) systems (Kourie, 2017 a, b) [Fig's 2 and 3] producing reduced waste streams of highly concentrated nutrient emissions well suited for integration into crop irrigation systems. Farmed tilapia species stand out offering the greatest food security impact potential as an alternative white fish species to that of cod, haddock, Alaskan Pollock, hake's, hoki etc. (Fitzsimmons, 2000; Kumar and Engle, 2016; Kourie and Dladla, 2022).

Reduced water footprint RAS and BFT enables easy integration of tilapia culture into existing crop irrigation systems generating significant usable nutrients for direct fertigation of a myriad of plant crops. A RAS tilapia grow-out production unit typically would generate around 368m3 of waste water/tonne of fish production while a BFT tilapia production unit would generate 150m3 of waste water/tonne of tilapia produced Kourie, 2017 a, b, d). Again, water use is non-consumptive given the sequential re-use of water for crop irrigation simultaneously adding substantial nutrients to the waste stream.

Table 1 provides useful benchmarks for discharged solid wastes (around 50% carbon on a dry matter basis), Nitrogen (N) and Phosphorus (P) emissions reported as kilograms (kg) per tonne of tilapia produced for tilapia cage culture installed into farm reservoirs as well as RAS and BFT tilapia culture to guide farm planning and the scaling of fish production units.

The advantages of IAAS compared to livestock-crop integrated systems, where livestock urea recovery is less practical, include two sources of recoverable nutrients from RAS and BFT tilapia aquaculture units, notably:

1) Dissolved nutrients readily available for plant growth applied either via direct fertigation of waste streams in crop irrigation or fertigation streams using a blend of dissolved chemical fertilizer and fish culture waste streams from a blending tank into irrigation systems allowing for more accurate nutrient dosing to irrigated crops.;

2) Fish culture solid wastes which will accumulate in settlement systems may be applied either by a slurry tanker pulled by a tractor, or centre pivots and sprinkler irrigation under adjusted solids concentrations, or dried and applied as a soil amendment, or a combination of dissolved nutrients and solid wastes in discharge water. High carbon solid wastes can be applied as a soil amendment.

The complete elimination of the use of chemical fertilizers is not advisable in view of the delayed availability of nutrients to plants associated with the solid fraction of animal manures including fish culture solid wastes. However, a partial organic fertilization strategy of around 50% offers improved soil health, reduced nitrogen (N) losses and improved economic returns.

Several studies have shown a 50% organic: 50% inorganic N fertilization strategy to yield near equivalent or better yields in irrigated plant crops (Tang et al., 2022) and reduced N losses through nitrous oxide (N2O) and nitric oxide (NO) while improving soil health and sustainability (Tang et al., 2022; Salinas et al., 2024; Wang et al., 2024).

Then, aiming for half the N to be sourced from fish culture effluent and the remaining half from chemical fertilizers with final balancing of phosphorus and potassium and other micro nutrients supplied by chemical fertilizers, tuned for crop requirements, seems the most sensible starting strategy with adjustments concluded on a local farm level following monitoring.

The benefits of an IAAS managed as a side stream project built into existing irrigated crop farms using the same water supply for fish and subsequently for crop irrigation would cut nitrogen based fertilizers costs by half (based upon half of nitrogen fertilization derived from fish culture effluents), produce affordable fish for local communities and markets, and go a long way to remedying the shortfall of affordable fish (Kourie, 2017d; Kourie and Dladla, 2022) given widespread adoption of IAAS by existing crop irrigation farming practices.

Cost sparing benefits of IAAS – a look at nitrogen fertilization

Assuming an annual nitrogen (N) fertilization rate of 200kg/Hectare (ha) in an orange orchard applied consecutively through the year using urea (46%N). Then, the total application rate over a year would amount to 434.8kg of urea/Ha [434.8kg urea =

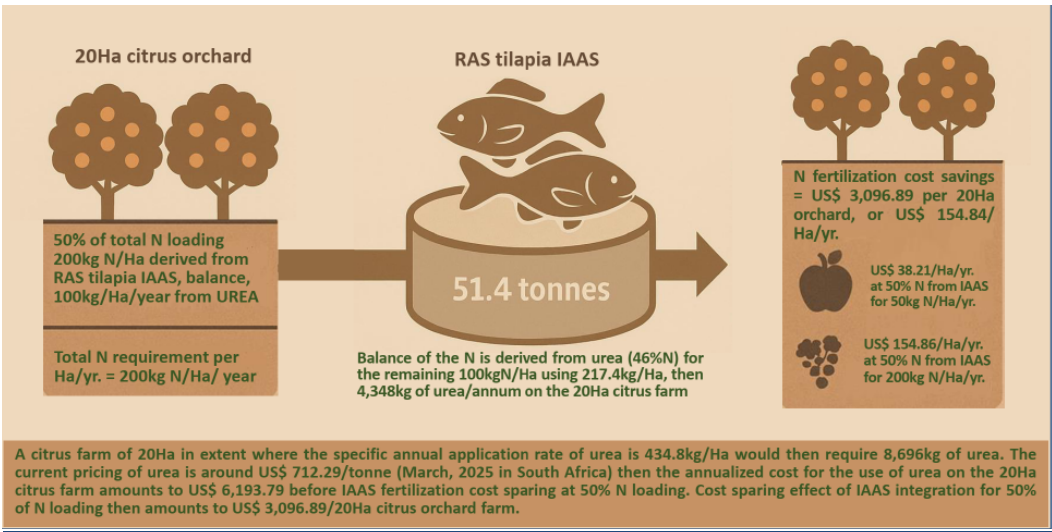


Figure 6: Cost-sparing benefits of IAAS – a look at Nitrogen fertilization

200kgN/(46%N/100)].

A citrus farm of 20Ha in extent where the specific annual application rate of urea is 434.8kg/Ha would then require 8,696kg of urea. The current pricing of urea is around US$712.29/tonne (March, 2025 in South Africa) then the annualized cost for the use of urea on the 20Ha citrus farm amounts to US$ 6,193.79.

Assuming the integration of a tilapia RAS farm into the citrus farm to create a tilapia → citrus IAAS how many tonnes of tilapia production would be required to provide 50% of the N fertilization loading in a 20Ha orange orchard? Half the loading of N fertilization for the 20Ha orange orchard amounts to 100kgN/ha where the balance is derived from urea (46%N). Then, 20Ha X 100kgN/Ha. = 2,000kgN. Using the value for N waste in a tilapia RAS from Table 1 of 38.9kgN/tonne of tilapia produced in a RAS we then need 51.4 tonnes of tilapia production to generate the required 2,000kg of N waste.

The balance of the N is derived from urea (46%N) for the remining 100kgN/Ha which amounts to a usage of 217.4kg/Ha of urea computed at 4,348kg of urea/annum on the 20Ha citrus farm at a cost of US$ 712.29/tonne which then amounts to US$ 3,096.89. Then some US$ 3096.89 in costs for the use of urea (46%N) has been spared through the integration of a 51.4 tonne RAS tilapia farming unit creating a IAAS built into a 20Ha citrus farm.

An apple orchard receiving 50kgN/Ha/year would then save US$ 38.71/Ha given 50%N sourced from a tilapia RAS or BFT farm. While a vineyard receiving 200kgN/Ha/year would spare US$ 154.86 /Ha per year given 50% of N fertilization derived from tilapia produced in a RAS or BFT. These estimates originate for the use of urea (46%N) as the sole N fertilization source.

Although only determined for N fertilization in the examples above tilapia waste streams contain a full spectrum of nutrients which amplifies savings when considering all the macro and micro nutrients. The agroecological benefits and economic opportunities IAAS offers commercial crop farmers include:

1) Significant savings in fertilization costs in irrigated crops and enhanced soil health attributed the SOM loading;

2) The production of an affordable source of aquatic protein for local communities at a cost potentially less than broiler chickens in the marketplace when raising tilapia in BFT systems generating an additional income stream using the same water supply volumes.

Perspectives

It will become increasingly essential to improve water productivity and nutrient circularity in the coming years in the light of a changing climate, droughts, and changing ocean conditions which impact both food- and seafood security particularly in water scarce regions. IAAS offers a very attractive solution to food (protein) insecurity mitigation with downstream benefits for farmers via a reduction in the use of fertilizers for irrigated crop production.

In summation then, IAAS offers increased soil microbial activity, increased soil carbon storage, elevated soil retention of water and nutrients, leading to increased crop yields and a reduction in the reliance on synthetic fertilizers, while sparing synthetic fertilization costs, and lastly improving overall agroecosystem health (Doran, 2002; Du Preez et al., 2011; Materechera, 2014; Okole et al., 2022; Derpsch et al., 2024). In addition, the circular economy principles introduced by IAAS herein aims to build value-preserving regenerative, resilient, non-wasteful and healthier food production systems in the agricultural sector through synergistic solutions to the growing global Supply-Demand gap for affordable fish, water scarcity and increased global food demand, and soil health and linked food security resilience.

Improving water productivity will be key to achieving the United Nations (UN) Sustainable Development Goals (SDG's) via the production of more food per unit of irrigated water volumes achievable via the adoption of IAAS. Aquaculture is of crucial significance given its potential benefits targeting all 17 SDGs (Troell et al. (2023), most evidently addressing hunger elimination and health promotion (SDGs 2 and 3); the responsible production and consumption of healthy crops to safeguard the environmental sustainability of terrestrial and aquatic biomes including the ocean and climate systems (SDGs 6, 12, 13, 14, and 15); and reductions in poverty and inequalities and improved livelihoods (SDGs 1, 5, 8, and 10). Then, based upon this contribution the development of sustainable RAS and BFT tilapia aquaculture systems grafted into new or existing irrigated crop production systems to create an IAAS, with improved nutrient circularity and enhanced water productivity, would score highest in terms of impactfully addressing all 17 SDG's offering almost unlimited aquaculture growth potential in the tropics and warm arid regions of the world to satisfy global fish demands to the year 2050 and beyond.

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Aquaculture

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Navigating the Shrimp Industry's Triple Challenge: Disease, Standards, and Sustainability

The global shrimp industry stands at a critical crossroads. Once defined by rapid expansion and export-driven growth, it now faces mounting pressure from three converging fronts: persistent disease outbreaks, increasingly stringent international standards, and rising consumer demand for environmentally responsible production. These challenges are not isolated but they are deeply interconnected, requiring a holistic approach that blends scientific knowledge, operational discipline, and strategic communication.

Shrimp farming has long battled a range of infectious diseases, from AHPND to WSSV and EHP. Despite advances in diagnostics, genetics, and closed-system technologies, disease remains an ever-present risk. In recent years, new threats have emerged, such as Translucent Post-Larva Disease (TPD), which some refer to as "Super EMS" due to its suspected link to Vibrio parahaemolyticus. These evolving pathogens underscore the importance of continuous surveillance, adaptive biosecurity protocols, and collaborative research across borders.

Why disease persist?

- Vertical transmission from broodstock: Pathogens can be passed from parent shrimp to offspring, especially when broodstock screening is insufficient or when latent infections go undetected. This silent transmission can seed disease into hatcheries before symptoms appear.
- Horizontal transmission within and between ponds: Disease can spread rapidly through water exchange, shared equipment, or direct contact between infected and healthy shrimp. Poor pond separation, inadequate disinfection, and movement of live animals without quarantine protocols all contribute to horizontal transmission risks.
- Fresh feed: Using raw or poorly treated feed, such as polychaetes, mollusks, or other crustaceans, can introduce harmful bacteria or viruses. Some microbes, including certain Vibrio species, exploit other aquatic organisms as carriers or amplification hosts, increasing the risk of cross-species transmission.
- Environment: Shrimp diseases are influenced by water quality, stocking density, feed practices, microbial balance, and fluctuation in temperature or salinity. Even in closed or recirculating aquaculture systems (RAS), pathogens can enter through broodstock, equipment, or human activity. Pathogens can persist in pond sediments, biofilms and surrounding water bodies, forming reservoirs that are difficult to eliminate. Inadequate disinfection may allow these opportunistic microbes to survive and re-emerge, especially when shrimp are exposed to environmental stress or weakened immunity.
- Stress Amplification: Shrimp are highly sensitive

to environmental stress. Minor disruptions, such as handling, grading, or sudden weather changes, can trigger immune suppression and disease outbreaks.

Strategic disease management: No single intervention can fully eliminate disease risk. To safeguard shrimp health, farms must implement a multi-layered biosecurity strategy by combining physical barriers, routine monitoring, feed and water management.

- Physical Barriers: Control access zones and apply solid disinfection protocols to reduce external contamination. Filtration system must include proper sludge handling and effluent treatment. Sludge collected from filtration units, skimmer system or pond sedimentation should be regularly remove and treat to prevent anaerobic decomposition and pathogen buildup.
- Routine disease monitoring: Regular sampling for pathogen load in both water and shrimp is essential for early detection and control. Swab tests of equipment, tanks, and pipelines help identify contamination hotspots, while scheduled PCR testing provides precise diagnostics for specific pathogens. Having an in-house laboratory or access to a nearby private lab is a major advantage, it allows farms to detect potential disease threats at the onset, even before clinical signs appear or infection spreads. This early warning capability enables faster response, targeted treatment, and better protection of stock health.

- Natural immunity support: The use of probiotics, from hatchery through to grow-out stages, offers significant benefits for shrimp health by enhancing nutrient absorption, stabilizing gut microbiota, and supporting defense against infections. Immunostimulants further strengthen the shrimp's immune system, helping to reduce the severity of disease impact and improve overall resilience under stress conditions.
- Emergency protocol A clear and prompt action plan must be in place to respond to disease outbreaks or contamination events. This includes immediate isolation procedures, targeted treatment, communication with farm staff. This could help to minimize production losses and prevent further spread.
- Farm management: All farm operations, from feeding and water exchange to health checks and equipment use, must be thoroughly documented and traceable. Accurate records support disease investigation, regulatory compliance, and continuous improvement in farm performance.

However, disease management is not just a farm-level issue. It must align with broader regulatory frameworks and export requirements. Global shrimp trade is governed by a complex web of standards ranging from national food safety laws to private certifications like ASC, BAP, and Global G.A.P. These standards cover everything from antibiotic residues and traceability to labor rights and environmental stewardship. Farmers may use antibiotics in shrimp farming as a means to treat bacterial infections, particularly in intensive systems where disease pressure is high. Antibiotics can offer short-term benefits such as rapid disease suppression, reduced mortality, and ease

Squid meat is a rich source of cholesterol and high-quality protein (>80%), supporting shrimp growth and reproduction; however, live or fresh feeds like squid, polychaetes, artemia, and mollusks may carry EHP and should be pasteurized at 70°C for 15 minutes or frozen at -20°C for 48 hours to eliminate infective stages.

Routine disease screening by real time PCR

of application through feed or water. However, their use comes with significant drawbacks. Improper dosing or failure to observe withdrawal periods can lead to residue accumulation in shrimp tissue. Export markets such as the EU, US, and Japan enforce strict Maximum Residue Limits (MRLs) for veterinary drugs and contaminants. Non-compliance can lead to shipment rejection and reputational damage.

The database, compiled by the Southern Shrimp Alliance, consolidates publicly disclosed information from enforcement agencies in the United States, European Union, and Japan. It tracks all shrimp products refused entry due to the detection of banned antibiotics and other antimicrobials.

Shrimp products are frequently rejected at international borders due to the detection of prohibited or excessive levels of antibiotic residues. Export markets such as the United States, European Union, and Japan enforce strict regulations to protect consumer health, with particular focus on substances known to pose serious risks. The use of chloramphenicol, nitrofurans, and triphenylmethane dyes is universally banned across all major markets due to their carcinogenic and toxic effects.

To ensure compliance, regulatory agencies have established Maximum Residue Limits (MRLs) or Target Testing Levels for various antimicrobial compounds.

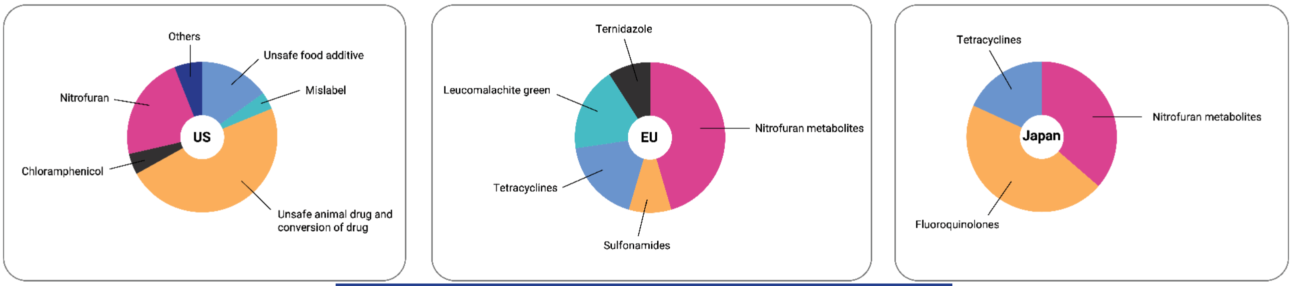
Overuse of antibiotics in shrimp farming contributes significantly to the development of antimicrobial resistance (AMR), making future disease outbreaks harder to control and posing broader risks to public health. AMR is an escalating concern in aquaculture, particularly in systems where antibiotics have historically been used to manage bacterial infections. It occurs when bacteria evolve to survive antibiotic exposure, rendering treatments ineffective and increasing the likelihood of persistent, hard-to-eradicate infections. These resistant microbes can persist in pond sediments, biofilms, and surrounding water bodies, and may spread between farms through water exchange, shared equipment, or live animal movement. Residual antibiotics also disrupt pond microbiota and damage surrounding ecosystems, compounding the environmental impact. Resistant bacteria can enter the food chain, compromise the effectiveness of veterinary and human medicines, and trigger trade restrictions. While AMR testing is not yet mandatory for seafood entering most export markets, it is expected to become a regulatory requirement in the near future. This growing pressure underscores the need for farms to adopt not only responsible antibiotic practices but also broader environmental responsible ensuring that disease control measures do not compromise ecosystem health or long-term sustainability.

Today's consumers are not just buying shrimp but they are concerning over carbon footprint, water use, and waste discharge are shaping purchasing decisions and brand loyalty.

•Carbon emissions: Energy consumption from aeration, water pumping, and transportation contributes significantly to greenhouse gas emissions in shrimp farming. Transitioning to solar-powered aerators, high-efficiency motors, and smart control systems can substantially reduce energy use and lower the farm's carbon footprint. However, the largest source of CO_2 emissions in aquaculture stems from feed production. The feed industry is under growing pressure to minimize its environmental impact, particularly regarding deforestation, greenhouse gas output, and resource-intensive manufacturing. Measuring the carbon footprint of feed products is a critical first step toward meaningful emission reduction. Feed producers face complex challenges in mitigating CO_2 emissions across the supply chain, from raw material sourcing and formulation to processing and distribution. Addressing these issues is essential not only for climate responsibility but also for aligning aquaculture with global sustainability standards and consumer expectations.

• Waste elution: Waste Elution: Effluent from shrimp farms often contains organic matter, nitrogen, phosphorus, and residual chemicals that can degrade surrounding ecosystems if not properly managed. Untreated discharge may lead to eutrophication, algal blooms, and loss of biodiversity in

Optimized feeding reduces overfeeding and minimizes organic waste buildup, lowering disease risk in intensive shrimp culture systems.



Shrimp entry line refusal by Unites States, European Union and Japan in 2024

nearby water bodies. In addition to waterborne waste, farms must also address the disposal of mortal shrimp from disease outbreaks, which pose a biosecurity risk if left unmanaged. Dead shrimp should be promptly removed and disposed of through safe methods such as deep burial, incineration, or controlled composting, depending on local regulations and disease severity. Another critical concern is the presence of antibiotic residues in pond sludge and effluent, especially when banned or high-risk substances have been used. Farms must implement sludge treatment protocols, effluent filtration systems, and routine residue monitoring to ensure that discharge meets environmental and regulatory standards.

• Land use and biodiversity: Conversion of mangroves or natural habitats for shrimp ponds remains a contentious issue in some regions. Modern aquaculture is shifting toward more sustainable land use models, including urban and high-tech closed system farming schemes that minimize environmental impact. Urban aquaculture offers a viable alternative by reducing pressure on natural habitats, improving resource efficiency, and enabling production closer to consumption centers. These innovations not only protect biodiversity but also align with climate resilience, land optimization, and circular economy principles.

The shrimp industry is under pressure, but it is also evolving. By embracing integrated disease management, rigorous compliance, and environmental responsible, producers can not only survive but lead. The path forward requires collaboration, innovation, and above all, clarity. When science is made accessible and standards are met with purpose, the industry becomes not just safer and cleaner but stronger.

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Animal Drug Residue	Target Testing Level or Tolerance Level (ppb) by US-FDA[1]	Maximum level (ppb) by EU[2]
Chloramphenicol	0.15	0.15
Nitrofurans	0.5	0.5
Triphenylmethane Dyes	0.5	0.5
Sulfonamides	10	100
Tetracyclines	2000 (sum)	100 (each)
Fluoroquinolones	5.0	100 - 300

Table 1. Maximum residue limits of antibiotic residue in shrimp tissue by US-FDA and EU

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Aquaculture Europe 2025: Valencia Hosts the World's Most Ambitious Ocean Farming Conference

When over 3,000 marine scientists, aquaculture entrepreneurs, and sustainability advocates descended upon Valencia's gleaming Congress Centre this September, they weren't just attending another academic conference. They were participating in what organizers proudly declared the largest aquaculture gathering in European history, a four-day showcase of how humanity might feed itself from the seas without destroying them in the process.

The European Aquaculture Society's annual conference has grown steadily over its decades-long history, but the 2025 Valencia edition broke all records. With 3,115 participants from 97 countries converging under the optimistic banner "Aquaculture for Everyone," the event generated more than €2 million in economic impact for the Spanish city while demonstrating that ocean farming has evolved far beyond simple fish pens.

Valencia wasn't chosen arbitrarily as the host city. Spain's Mediterranean coastline leads the nation in marine aquaculture production, generating 14,575 tonnes annually of sea bream, sea bass, and other species. The region has invested heavily in blue economy research through a €10 million initiative involving 39 research groups and over 370 scientists from Valencian universities. This conference represented the culmination of that investment, with researchers presenting breakthrough findings in everything from artificial intelligence-guided feeding systems, fish and shrimp nutrition to climate-resilient fish breeding programs.

The scientific heart of the gathering lay in its unprecedented scope: 1,254 research abstracts transformed into 597 oral presentations and 571 electronic posters across 57 specialized sessions. Unlike many academic conferences where sessions run simultaneously in isolated rooms, Valencia's organizers designed an interconnected program where discoveries in fish genetics informed discussions about sustainable feed development, which in turn influenced conversations about offshore farming technologies.

Three world-renowned keynote speakers set the intellectual tone for these discussions. Carlos Duarte from Saudi Arabia's King Abdullah University opened the conference with a vision of "regenerative aquaculture"—farming practices that don't merely sustain marine ecosystems but actively restore them. His presentation challenged the industry to move beyond simply reducing environmental damage toward actively healing oceanic environments while producing protein for growing populations.

Elisabetta Giuffra from France's INRAE research institute followed with groundbreaking insights into genomic technologies that could revolutionize how quickly fish breeders develop climate-resilient stocks. Her work promises to compress breeding timelines that traditionally required decades into periods measured in years, potentially allowing aquaculture to adapt to changing ocean conditions faster than climate change can outpace it.

Perhaps most sobering was the final keynote from consumer research expert Joan Riera, who presented data showing declining seafood consumption across Europe despite mounting evidence of its health and environmental benefits. His analysis revealed a troubling disconnect between scientific consensus on sustainable protein sources and consumer behavior—a gap the industry must bridge to achieve its ambitious growth targets.

The conference's commitment to inclusivity extended well beyond its "for everyone" motto. Organizers accommodated 381 students alongside established researchers, while specially designed outreach programs introduced 90 local school children to aquaculture careers. This generational bridge building reflected growing recognition that today's sustainability challenges require solutions that span decades, demanding engagement from those who will inherit tomorrow's oceans.

Industry participation matched academic enthusiasm, with 155 corporate exhibitors filling nearly every available space in the Congress Centre's trade hall. Unlike traditional equipment-heavy exhibitions, this year's display emphasized software solutions, biotechnology innovations, and service platforms designed to make aquaculture more precise and environmentally responsive. Companies demonstrated Internet of Things sensors that monitor water quality in real-time, artificial intelligence systems that optimize feeding schedules, and blockchain platforms that trace seafood from farm to consumer.

Eight special industry forums addressed practical implementation challenges that often remain unexplored in purely academic settings. The Food and Agriculture Organization led discussions on translating sustainable aquaculture guidelines into enforceable regulations, while the Network of Women in Aquaculture hosted roundtables focused on developing industry talent from underrepresented groups. These sessions bridged the persistent gap between laboratory breakthroughs and commercial viability that has historically slowed aquaculture innovation.

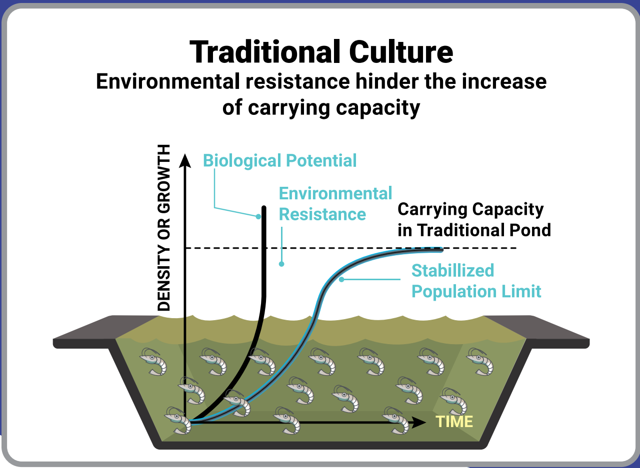
Offshore aquaculture emerged as a particularly compelling theme throughout the conference. As coastal waters become increasingly crowded and regulated, industry leaders presented evidence that moving fish farms into deeper, more exposed waters could dramatically expand production capacity while reducing environmental conflicts with tourism and traditional fishing. Norwegian companies shared operational data from offshore installations weathering North Sea storms, while Mediterranean researchers presented modeling studies suggesting similar systems could thrive in calmer southern waters.

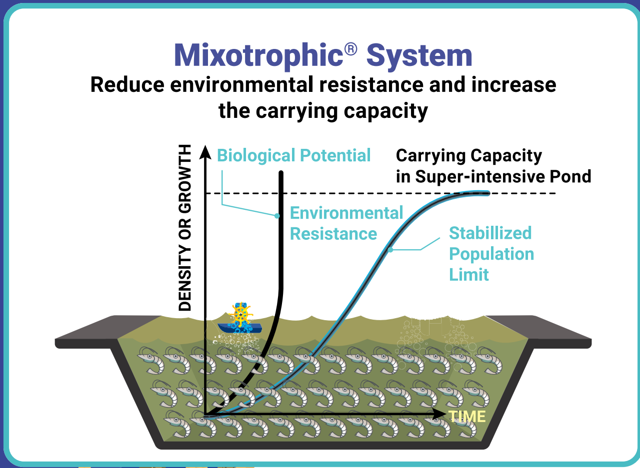
The conference's international character reflected aquaculture's global nature, with the strongest scientific contributions coming from Spain, Norway, Italy, Portugal, France, Germany, the United Kingdom, and South Korea. This geographic diversity proved crucial for addressing challenges that vary dramatically between Arctic salmon farms and tropical shrimp ponds. Solutions developed for Norwegian fjords might require significant adaptation for Mediterranean lagoons, but the underlying principles of sustainable intensification remain surprisingly consistent across ecosystems.

Government support for the conference extended far beyond ceremonial ribbon cutting. Spain's Ministry of Agriculture, Fisheries and Food used the gathering to announce new spatial planning initiatives designed to allocate marine areas for aquaculture expansion while protecting critical habitats. The Generalitat Valenciana presented updated regional strategies positioning the area as Southern Europe's aquaculture innovation hub, while representatives from Brussels outlined European Union funding opportunities for sustainable blue economy projects.

As delegates departed Valencia's palm-lined waterfront, many carried commitments to collaboration that extended well beyond traditional academic partnerships. Research groups announced joint projects spanning continents, while industry leaders finalized agreements to test promising technologies in diverse environments. The European Aquaculture Society announced that Ljubljana, Slovenia would host 2026's gathering, followed by Athens in 2027—ensuring this momentum continues building across the Mediterranean basin.

Valencia's success in hosting Europe's largest aquaculture conference reflected more than logistical competence; it demonstrated the region's emergence as a legitimate center for sustainable marine food production. With global population approaching 10 billion by 2050, and traditional fisheries already stressed beyond sustainable limits, the innovations showcased in Valencia's Congress Centre may prove essential for feeding humanity's future. The question is no longer whether aquaculture can scale to meet this challenge, but whether it can do so responsibly transform our relationship with the oceans from exploitation toward genuine stewardship.





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Practical Challenges in Shrimp Disease Management in India

Introduction

Global shrimp aquaculture production continues to reach new heights, with annual volumes rising steadily, driven by top-producing countries such as Ecuador, India, China, Vietnam, and Indonesia. Ecuador currently leads the sector with over 1.4 million tons per year, while India ranks second with close to 1 million tons. Despite this production growth, the economic value has not kept pace due to factors such as inflation, geopolitical conflicts, economic crises, and reduced demand from major importing markets like the US, EU, and Japan. Compounding these challenges, recent reciprocal tariffs from the US have dealt a significant blow to producing countries, particularly India, which now faces an additional 50% tariff on top of anti-dumping (AD) and countervailing duties (CVD). Additionally, shrimp diseases are a major concern for farmers, who face challenges both from production losses due to disease and from unstable farm-gate prices.

In India, the major diseases include White Spot Syndrome Virus (WSSV), Enterocytozoon hepatopenaei (EHP), and Vibrio-related infections, which together cause more than 30% damage to the production, while slow growth, white feces, and random mortality reduce potential production by more than 50%.

Biosecurity in Shrimp Farming: Physical, Chemical, and Biological Measures

Physical barriers in shrimp farms typically include fencing to prevent birds and other animals from entering the premises. While most shrimp farms in India are already equipped with such protective measures, the key challenge lies in continuously monitoring and maintaining their effectiveness. Nets and strings installed around extensive open ponds often require frequent repairs due to prolonged exposure to sunlight and physical wear, which can lead to significant security breaches and allow potential disease carriers access to the pond. Understanding the fundamental purpose of these fences is crucial—they must be regularly inspected for efficiency, and any deficiencies should be addressed immediately. Maintaining such robust biosecurity demands sustained interest, patience, and adequate financial support.

Chemical measures in shrimp farms involve standardized treatment protocols for soil, water, and equipment disinfection, as well as for maintaining sanitation and hygiene. Commonly used biosecurity chemicals include strong oxidizing agents such as chlorine (in the form of bleaching powder), potassium permanganate, iodine, hydrogen peroxide, potassium monopersulfate (commonly called triple salt), benzalkonium chloride (BKC), and others. Each chemical has a distinct mechanism of action, and the choice of treatment depends on the type of pathogen and the target surface or medium to be disinfected. For optimal effectiveness, the lethal dosage, contact time, and method of application must be carefully designed. Often, this critical aspect is overlooked, rendering the treatments both ineffective and costly, which can ultimately result in crop failure.

Biological measures in shrimp farming focus on modifying the pond ecosystem to suppress pathogenic bacteria. This is achieved through bioremediation using prebiotic and probiotic bacteria that establish dominance in the pond environment, leaving little opportunity for harmful microbes to proliferate. Regular application of fermented rice bran enriched with probiotics improves water quality, while sulfur-utilizing photosynthetic bacteria help manage pond bottoms by reducing organic load accumulation, thereby discouraging pathogenic growth. Careful selection of probiotic strains that can naturally thrive in the pond environment is essential. Additionally, some farms employ fish as natural cleaners to feed on benthic algae, unwanted organisms, or other undesirable animals in the pond.

Importance of disease diagnosis

Abnormal shrimp behaviour, erratic swimming, leaning on dykes, or dead animals with cannibalized appendages should trigger immediate diagnostic testing. Most often, farmers are worried about the abnormal shrimp; they immediately bury them to avoid further contamination. But this one small misjudgment could cause severe lapses in disease diagnosis and may lead to a severe outbreak of disease. There should be a quick response to safely collect these particular animals and, based on the symptoms, test for known pathogens at a well-equipped real-time PCR laboratory, or at least with on-site lateral flow kits.

Disease Mitigation and Action Plans
WSSV control action plan:

Once the white spot disease outbreaks in one or a few ponds, many farmers react by applying pond sanitizers to reduce the chance of contamination. This may seem good as a disease prevention protocol, but it may not serve the primary purpose, as these sanitizers can only kill free-living virus particles. It is always suggested to improve biosecurity practices rather than depending on expensive package products to control the spread of disease.

On confirmation of WSSV, immediately restrict movement and isolate the infected pond by fencing and spraying strong disinfectant (fig 1). Assign dedicated personnel to the pond and prevent the entry of birds or animals.

A quick decision must be made: **harvest or terminate**.

• **If shrimp are marketable size:** chill-kill on site by placing harvested shrimp in ice, pack in leak-proof containers, and transport carefully. Ensure nets are cleared, and workers must bathe before leaving the farm.

• **If shrimp are too small:** terminate with proper chlorine dosing, stop aeration, and wait until complete mortality. Prevent bird and animal entry for 7–10 days.

Lockdown the farm:

Movement spreads disease—water, aerators, people, or birds can carry it. Declare a farm lockdown and restrict all movement:

• **Red flag (first 7 days):** Only essential tasks like feeding and aeration are allowed, with strict disinfection of hands and feet.

• **Orange flag (days 8–14):** If no spread is observed, essential farm operations can continue.

• **Green flag (after 14 days):** With no further spread, normal operations may resume.

The infected pond can be dried or disinfected after 21 days and prepared for restocking. If additional ponds become infected, the lockdown protocol must be repeated until the infection cycle is broken.

Mandatory physical lockdown, proper understanding of disease movement, and patience are crucial to prevent contamination within and between neighbouring farms

EHP:

Fig 1: Pond isolation

Fig 2: Vibrio-EHP

Understanding EHP Infection Cycles

EHP spores upon recognizing the host cell receptor protein on the hepatopancreatic cells, then release sporoplasm by extrusion of the long coiled polar tube. EHP is an obligate intracellular parasite, lacks its own energy and metabolic functions, redirects the total mechanism for its own proliferation in the host cell, thereby weakening the host cell and damaging it, and reinfects new hepatopancreatic cells. Hepatopancreas has the most vital functions, like nutrient metabolism, digestion, storage, and assimilation. When this organ is infected, shrimp lose appetite and stop feeding. Even if feed consumption remains stable, the nutrients are not properly digested and assimilated. Shrimp cannot molt and grow actively, and shrimp become weak; the immune system is compromised, providing free access to opportunistic Vibrio and other pathogenic bacteria to colonize. The toxins produced by these bacteria further damage the hepatopancreatic cells, which are drained along with the stored lipids and other nutrients through the intestine, thus the infected animals appear with a white gut and the excreta floats on the water surface as white feces. Infected shrimp show the symptoms of weakness, discoloration of the body, (fig 2) often with opaque and soft muscles, turns loose shell, and eventually die. The symptoms may appear from the early stage of infection, but shrimp mortality may go unnoticed or often be confused with random mortality.

Diagnosis and decision-making for EHP-infected ponds is challenging because the early signs and symptoms are nonspecific, such as slow growth and size variation. At this stage, it is often difficult to suspect a potential infection, and the symptoms may be overlooked until the disease has progressed. EHP infections are frequently accompanied by secondary infections from opportunistic pathogenic bacteria. In severe cases, clinical signs may escalate to white feces, soft or loose shells, and sporadic mortality.

In the pond environment, EHP exists in strong and highly resistant spore form, the one and only infective, extracellular life stage, protected by a proteinaceous exospore and chitinous endospore. These spores can thrive in free-living form without a host or carrier for years in the soil, water, and biofilms. Polychaetae worms, mollusks, and abiotic surfaces like equipment, pipes, and sludge are understood to be passive carriers.

Immunostimulants, growth promoters, probiotics, and herbal remedies may help to reverse the condition and improve shrimp health only until the early stages. Feed consumption analysis by strict and true check tray monitoring can give a clear picture of the pond's response to EHP infection. If the shrimp's health,

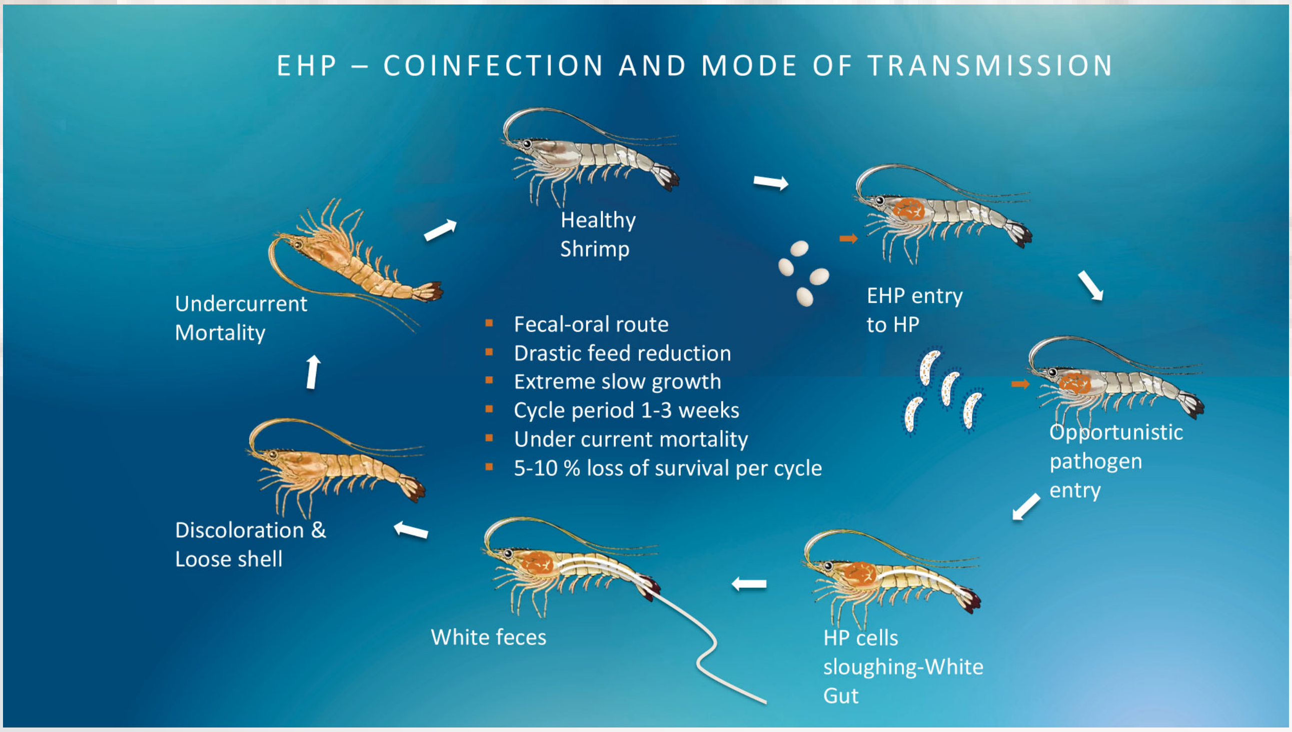

Fig 3: EHP cycle

feed consumption, and growth do not improve at this stage, the condition may be irreversible, and the disease progresses intensely. Depending on the initial spore load, density of shrimp, external triggering factors, bacterial communities in the stomach, intestine, and shrimp immune response, the infection cycle progresses in a population to close with 3-5% undercurrent mortality. Frequent episodes of this cycle may lead to a drastic reduction in feed intake, and further continuation of the crop may lead to severe loss of survival some sometimes up to 60-70% (fig 3).

Mitigation strategies for EHP-infected pond:

1. Proceed with caution: No visual symptoms like white feces, loose shell, or mortality

• Feed consumption matches with weekly growth performance; the shrimp health status can be reviewed every week.

2. Alarming situation: Visual white feces appear, but no loose shell or mortality so far

• If the feed consumption is good but is not reflected in weekly growth, FCR may go high.

• If the feed consumption is less but the weekly growth performance is better, survival may be reduced.

In both cases, assess shrimp biomass and present market price, and it is advised to take a harvest decision whenever the balance sheet is either break-even or marginal profit.

3. Emergency situation: Severe white feces, Loose shell, or Mortality

• If the feed consumption is less but the weekly growth is still good, survival may drastically reduce.

• The feed consumption may be good or not, but weekly growth is poor, survival may reduce, and FCR may drastically increase.

In both cases, irrespective of the balance sheet, it is advised to harvest immediately to avoid severe crop loss.

The most important observation is the recurrence of loose shell and running mortality symptoms, which appear for a while and later, with or without treatment, while sampling the shrimp may look healthy, and this kind of response from the pond may raise false hope of recovery. Farmers tend to increase the feed and feed additives to save the crop, and this in turn worsens the situation by prolonged culture with additional input costs.

In summary, as the days of culture progress post-infection, the key pond performance indicators are affected; feed consumption, weekly growth, and survival may decrease, but at the same time, FCR, production costs, and spore load may increase too. It is very important to have a record of these performance indicators in hand during shrimp sampling, and if the indicators mismatch, the decision to harvest must be considered seriously. Timely decision at the most crucial point based on the present size and market price of shrimp is the key to saving the crop and reducing losses (fig 4).

EHP and Vibrio, the Pathobiome

While EHP alone can cause remarkable damage to the pond performance, it is well established that with a coinfection of

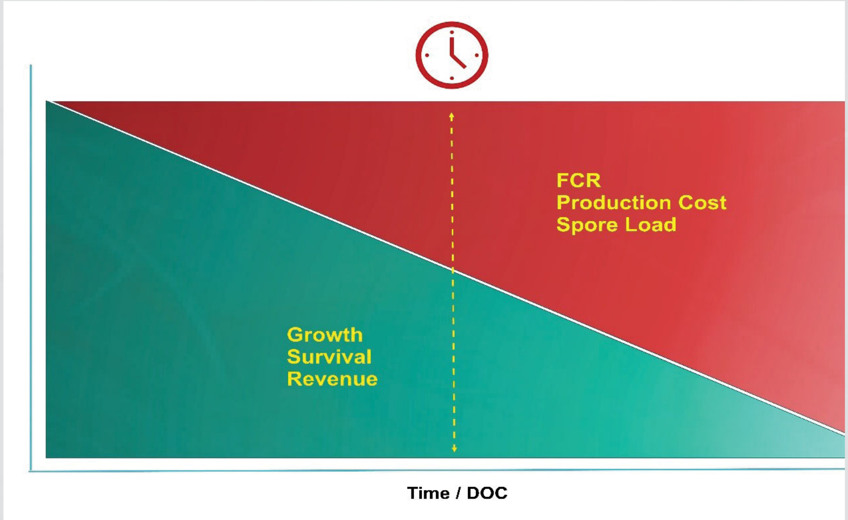

Fig 4: Timely decision

EHP with opportunistic Vibrio and other pathogenic bacteria like *Photobacterium damselae, Propionigenium* Sp., etc, the damage can be multifold.

While many Vibrio species are normal flora in the culture environment, a few opportunistic Vibrio can turn pathogenic when the pond environment or the shrimp's immune system is compromised. For this reason, farmers are advised to regularly monitor Total Vibrio Count on chromogenic vibrio media on which at least 4 pathogenic Vibrio species can be identified and enumerated. Experts suggest regular use of probiotics to maintain microbial mature water, rich in probiotic bacterial communities, which compete and dominate total vibrio numbers by 10-fold.

Disease eradication measures:

Some of the research findings published in Bioassay for spore polar tube extrusion by Dr. Kallaya Sritunyalucksana and other eminent scientists, Centex shrimp, Mahidol University, helped us to formulate treatments to control and eradicate EHP at the hatchery and farm level (fig 5).

While treatment and eradication for these diseases vary due to pathogen biology, the high strength and dose of treatments prescribed for EHP spores can effectively eradicate other pathogens like WSSV and Vibrio, too. Choice of treatment method, dose, and contact time is well considered based on the target subject for treatment. Maintaining the treatment chemical dose for the prescribed contact time in every inch of the pond is the most challenging part. The practical possibility and financial feasibility of these treatments have to be considered while formulating treatments.

While most of the treatments proved to be effective against EHP spores, it is practically difficult to completely eradicate them from large open earthen grow-out ponds, as in India. We target to reduce the initial spore load in the environment, at least to a lower level, so that the next crop can be cultured until the planned harvest size.

PCR Screening and Diagnostic Challenges:

PCR screening for WSSV and EHP at different life stages—broodstock, nauplii, early PL, and before stocking—has proven to significantly reduce the risk of early disease outbreaks in grow-out systems. Inputs used in hatcheries, such as polychaete

Treatment	Dosage	Contact Time
Temperature	- 20^{0}C	2 hrs
	70^{0}C	10 min
Calcium Oxide / Sodium Hydroxide	> 9.0	NS
Acid (HCl)	< 4.5	NS
Chlorine (65%) active	40 ppm	15 min
	10 ppm	24 hrs
Potassium Permanganate	15 ppm	15 min
Formalin	200 ppm	NS
Ethanol	20%	15 min

Fig 5: EHP treatment

worms, biofilms, and fecal waste, play a critical role in disease introduction and must be carefully monitored.

Despite routine PCR testing of seed before stocking, farmers often doubt the sensitivity of PCR or the credibility of the laboratory during an outbreak situation. While ensuring sensitivity, specificity, and reproducibility of PCR is essential, one major challenge laboratories face is the risk of false negatives—where a positive sample may go undetected. This issue is not unique to PCR but is deeply linked to the statistical principles of sampling a population.

It is straightforward for any diagnostic system to detect infection when the sample is directly drawn from an infected individual. However, the challenge arises when the population size is extremely large, and the infection prevalence is very low. In such cases, the representativeness of the collected sample becomes critical. For this reason, it is recommended to test individual broodstock, their fecal waste, polychaete worms, or other fresh feeds before introducing them into the maturation tanks.

A single maturation tank with 3–5 broodstock can generate a population exceeding two million larvae. Proper egg washing can reduce potential disease risks if contamination arises from infected feces or feed sources. Once they are converted to post-larvae, the population becomes vulnerable to disease through input feeds such as fresh feeds, artemia, contaminated water sources, and biofilms within the system. At this stage, the prevalence of infection may be so low that only a handful of PLs out of millions are infected. Random sampling under these conditions increases the chance of missing infected individuals.

To overcome this, biased sampling methods are recommended. Samples should be collected from multiple points in a tank, pooled, and then processed. Swirling the water and collecting weak PLs that settle in the center increases the probability of detecting infections. Additionally, stressing the PLs by withholding feed and oxygen for a few hours can allow pathogens to multiply, thereby enhancing detection efficiency. Hatcheries are advised to perform PCR testing at multiple intervals to ensure disease-free seed production.

Farmers, on the other hand, should verify hatchery test records, tracing results from broodstock through to the final packing stage. A final PCR test—at least one per million PLs—should be conducted before seed procurement to confirm health status (fig 6).

It is important to recognize that the financial and practical challenges of crop loss at the farm level are significantly greater than those at the hatchery level. Therefore, both hatcheries and farmers must adopt a holistic disease control strategy to minimize the risks of WSSV and EHP in culture systems

The Way Forward: Building Resilient Shrimp Aquaculture in India

Despite the challenges posed by trade tariffs, increasing production costs, and recurring disease outbreaks, India's shrimp farmers continue to demonstrate remarkable resilience. The future growth of the sector will depend heavily on the adoption of sustainable farming practices, timely and effective disease management, and the implementation of strict biosecurity protocols. Equally important will be stronger collaboration between farmers and hatcheries, ensuring the consistent supply of healthy seed and the sharing of best practices across the value chain. Together, these measures can safeguard productivity, enhance profitability, and strengthen India's position in the global shrimp market.

Fig 6: Lab diagnosis

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The Hidden Backbone of Aquaculture: Why Fish and Shrimp Welfare Matters

Introduction

When people talk about aquaculture, the conversation often turns to technology, innovations, farm management through the Internet of Things, or sustainability certifications. What is less often acknowledged is the simple truth that underlies every successful system: the welfare of the animals themselves. Fish and shrimp welfare is not an afterthought- it is the backbone of aquaculture. Ignoring it not only compromises the ethical base of farming but also undermines productivity, efficiency, and long-term sustainability.

Each year, more than 100 billion fishes and several hundred billion shrimps are farmed worldwide, making them the most farmed animals on the planet by number (Animal Charity Evaluators). If welfare is ignored at this scale, the impact is immense: not just for the animals themselves but for everyone associated with the supply and value chain. This is why welfare has to come first, as the foundation on which everything else is built.

Fish and shrimp welfare is not an abstract concept. It is the quiet, everyday foundation of aquaculture. Animals under stress grow poorly, succumb to disease, and yield products that deteriorate faster. Animals kept in better conditions, handled carefully, and harvested humanely do not only "live better": they help farms achieve certainty in resilience against shocks, and acceptance in increasingly welfare-conscious markets.

Farmers across the world already shoulder enormous uncertainty - fluctuating prices, weather extremes, disease outbreaks, or sudden losses that wipe away months of effort. When survival itself feels uncertain, "welfare" can sound like a distant demand. But reframed correctly, welfare is not a burden. It is a set of minimum, practical steps that create steadiness. Every farmer knows that certainty is rare, but higher welfare can help bring it closer.

This article explores what welfare means in aquaculture, what science tells us about stress and resilience, and what practical changes across life stages from hatcheries to harvest, can make a difference. It looks separately at fish and shrimp, since their biology, farming methods, and welfare challenges differ. And it frames welfare not as an "extra" but as the backbone that links sustainability, profitability, and responsibility.

Why Welfare is the Backbone of Aquaculture

Welfare Defined

Welfare, at its core, refers to the state of the animal and its ability to live with minimal suffering and with conditions that allow it to thrive. In recent years, the classic "Five Freedoms" (freedom from hunger, discomfort, pain/injury/disease, fear/

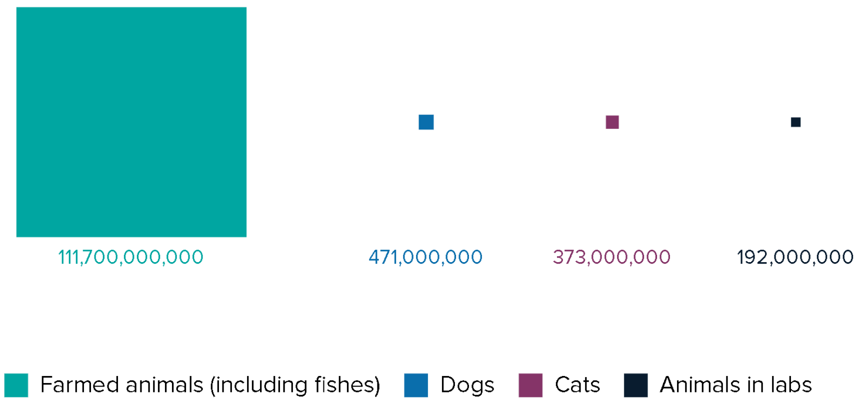

Figure 1: Domestic animal groups as a percentage of the estimated world population (Source: Animal Charity Evaluators)

distress, and freedom to express normal behavior) have evolved into the "Five Domains" model. The Five Domains broaden the focus:

1. **Nutrition** - access to appropriate feed and water.
2. **Environment** - quality of the surroundings: oxygen, space, shelter.
3. **Health** - protection from injury and disease.
4. **Behaviour** - ability to perform species-specific behaviors.
5. **Mental state** - the integrated outcome of the other four domains.

Applying this framework in aquaculture does not mean recreating the wild system, but building systems where fish and shrimps can live and grow without constant stress.

The Science of Stress

Fish and shrimp respond to stressors with measurable physiological changes.

- **In fish**, stress activates the hypothalamic-pituitary-interrenal (HPI) axis, releasing cortisol. Chronic cortisol elevation diverts energy away from growth and immunity, weakens resistance to pathogens, and reduces reproductive success. Handling, crowding, poor water quality, and air exposure are common triggers (Ellis et al., Fish Physiology and Biochemistry, 2012).

- **In shrimp,** stress shows in elevated hemolymph glucose, lactate, and changes in hemocyte counts. Environmental instability such as sudden salinity shifts, poor oxygenation, handling - weakens their immune system and increases susceptibility to diseases (Fotedar & Evans, Aquaculture, 2011).

From a science perspective, stress just before harvest causes lactic acid buildup in muscles. This lowers pH, accelerates rigor mortis, and reduces shelf life (Robb et al., Aquaculture Research, 2000). In other words, welfare is inseparable from quality.

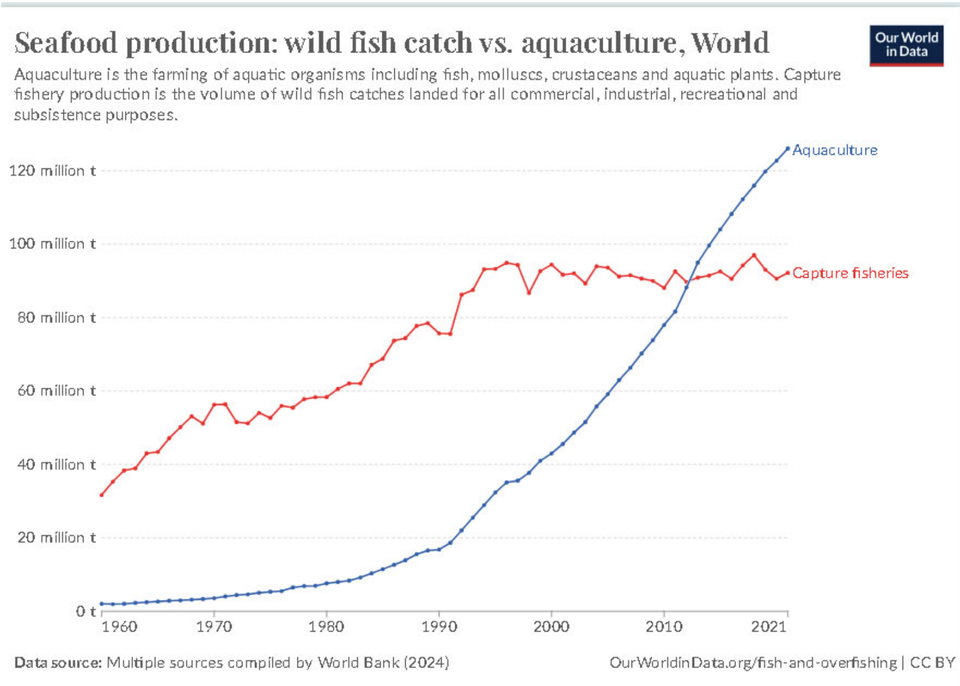

Figure 2: World seafood production: wild fish catch vs. aquaculture (Source: Our World in Data)

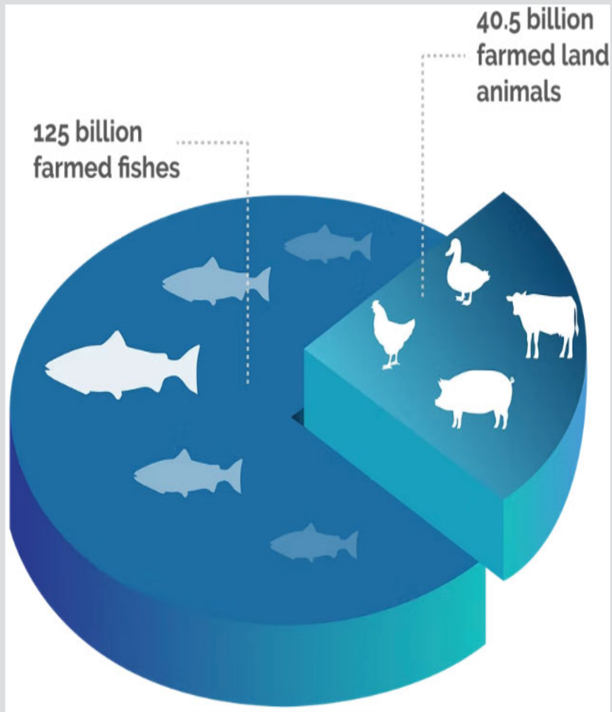

Figure 3: Estimated farmed vertebrate animals at any given point (Source: Fish Welfare Initiative)

Linking Welfare, Economics, and Certainty

For farmers, welfare practices are not just ethical choices. They are economic stabilisers. Reduced stress means:

- Lower mortality and steadier survival rates.
- More uniform growth, making harvest predictable.
- Less reliance on antibiotics and chemicals.
- Better shelf life and marketability of their harvest.

In markets increasingly conscious of sustainability and food safety, welfare adds an additional layer of certainty: it assures buyers that the system is future-facing, not stuck in older practices.

Fish Welfare Across Life Stages

Hatchery & Broodstock

Broodstock management sets the foundation for the entire production cycle.

- **Nutrition:** Balanced diets rich in essential fatty acids and vitamins improve egg quality, larval viability, and fry survival. Studies in common carp and tilapia show broodstock under nutritional stress produce weaker larvae (Izquierdo et al., Aquaculture, 2001).
- **Handling:** Gentle capture, minimal transfers, and avoidance of overcrowding during spawning reduce injury and stress hormone spikes.
- **Environment:** Stable temperature, oxygen, and reduced light fluctuations lower mortality in early larvae.

Early stress carries "life-long scars": fry exposed to repeated stress events often show suppressed growth and heightened disease vulnerability.

Nursery/Juvenile Stage

In juveniles, density is a double-edged sword. Too low wastes infrastructure; too high suppresses welfare.

- **Stocking density:** Research in Catla and Rohu shows moderate densities improve growth and reduce aggression, whereas overstocking elevates cortisol and disease outbreaks (Reddy et al., Indian Journal of Fisheries, 2017).
- **Enrichment:** Simple structures like pipes or mesh reduce aggressive encounters in some species, leading to steadier growth.
- **Water quality improvement:** Juveniles are especially sensitive to low dissolved oxygen and ammonia. Farmers who monitor daily, rather than waiting for signs like surface gulping, avoid preventable mortalities.

Grow-Out

This is the longest phase, where management consistency matters most.

- **Feeding:** Regular schedules and avoiding under/over-feeding, prevent competition and water deterioration. Uneaten feed not only wastes money but degrades dissolved oxygen.
- **Aeration:** Low oxygen is the single greatest stressor in grow-out ponds. Proper aeration (if feasible) reduces nighttime crashes, stabilises feeding behaviour, and lowers mortalities.
- **Behaviour as an indicator:** Fish surfacing in daylight or gather in unusual groups are signs that welfare is compromised. Farmers who notice these signs early can often fix the problem before it gets serious.

Harvest & Slaughter

Harvest is often the peak of stress but how it is done makes a big difference.

- **Handling:** Crowding fish into nets, prolonged air exposure, and rough transfers trigger spikes of the cortisol and muscle lactate. These biochemical markers shorten shelf life (Poli et al., Aquaculture International, 2005).
- **Humane killing:** Traditional asphyxiation in air or on ice is slow and stressful. Alternatives such as well-prepared ice slurry (for species suited to chilling) or electrical stunning provide faster loss of consciousness.
- **Market benefits:** Fish slaughtered with lower stress levels not only "die better" but also yield meat that consumers prefer. Studies in Atlantic salmon show humane stunning extends shelf life by several days (Robb et al., Aquaculture Research, 2000).

AI-generated image: Farmer gently harvesting fishes in a farm

AI-generated image: Shrimp harvest in a farm

Shrimp Welfare Across Life Stages

Hatchery & Broodstock

Shrimp hatcheries, particularly for penaeids, face high mortality risks.

● **Broodstock handling:** Gentle handling during breeding reduces injury and stress, which directly affect spawning success (Fotedar, Reviews in Aquaculture, 2019).

● **Larval rearing:** Maintaining stable salinity and temperature, avoiding sudden water exchanges, and providing balanced live feeds (algae, Artemia) reduce early-stage mortality. Stress in larvae often manifests in weak swimming and reduced feeding response.

Nursery/Juvenile

Shrimps are particularly sensitive to crowding and water instability.

● **Density:** Overstocking juveniles elevates competition, weakens immunity, and raises cannibalism rates. Shrimp stocked at moderate densities show steadier growth and higher survival (Arnold et al., Aquaculture Research, 2006).

● **Water quality:** Juveniles show strong sensitivity to ammonia-N levels. Hemolymph analysis indicates increased lactate under poor water, reflecting stress (Fotedar & Evans, 2011).

● **Substrate use:** Adding substrates provides surface area, reduces aggressive encounters, and promotes natural grazing behaviour.

Grow-Out

For shrimp, grow-out ponds are where welfare failures quickly become disease outbreaks.

● **Oxygen and water stability:** Shrimp cannot tolerate dissolved oxygen crashes or sudden swings in water quality. Even short dips in oxygen or sharp changes in temperature, pH, or salinity weaken their feeding and immunity, making them prone to disease and sudden mortalities.

● **Feeding:** Poor feeding practices stress shrimps. Overfeeding ruins water quality, while underfeeding increases aggression and cannibalism. Spreading feed in multiple areas and observing how quickly it's eaten reduces stress and keeps the pond balanced.

● **Behaviour cues:** Shrimp resting near pond edges, swimming erratically, or reduced feed intake are early signs of stress. Addressing them early prevents mass losses.

Harvest & Slaughter

Shrimp harvesting practices often rely on ice, but this is not straightforward.

● **Traditional ice killing:** Placing shrimps directly on ice can take minutes for death, during which stress and activity continue. This also depletes energy reserves and reduces shelf life.

● **Improved chilling:** Well-prepared ice slurries reduce the time to unconsciousness. Emerging methods such as electrical stunning show promise for crustaceans but need scaling.

● **Product quality:** Shrimps handled gently and chilled effectively retain firmer texture and brighter color, with less melanosis. That translates directly to better prices in markets.

Certainty for Farmers, Trust for Consumers

Aquaculture is a sector full of unpredictability: changing climates, disease outbreaks, volatile markets. For many farmers, the question is not "how much profit?" but "will this farm still be running next year?"

Implementing higher welfare practices offers a measure of certainty:

● **For farmers:** steadier survival, predictable growth, lesser diseases, and reduced sudden losses.

● **For markets:** better shelf life, safer chemical profile, no/ lesser antibiotics, and traceability.

● **For consumers:** assurance that the source from where they eat is not only sustainable in name but also in practice.

Welfare also bridges trust across the supply chain. Scientists can point to measurable benefits. Activists can recognize progress. Farmers can see reduced losses. Consumers can taste and trust the difference.

It is not about "forcing" welfare into systems but recognizing it as the baseline for aquaculture's future.

Conclusion

AI-generated image: Healthy aquaculture ponds with a farmer smiling beside aerators

When we strip away the jargon, aquaculture is about living beings- fishes and shrimps that, like any farmed animal, respond to how we treat them. Welfare is not an extra layer placed on top of production; it is the backbone that holds it together.

From broodstock nutrition to handling at the time of harvest, each stage offers small but significant opportunities. Managing dissolved oxygen, handling carefully, reducing crowding, observing behaviour are the minimum steps that create resilience. And in a sector as uncertain as aquaculture, resilience is survival.

Respecting welfare is not just about ethics. It is about ensuring farms can last, systems can be trusted, and the future can be sustainable. For the farmer, the consumer, the researcher, and the animal - "welfare" is the quiet partner we can no longer ignore.

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FUTURE AQUACULTURE

Events

Upcoming Aquaculture and Fisheries Conferences and Exhibitions:

World Seafood Congress 2026

- Dates: February 9–11, 2026
- Location: Chennai Trade Center, Chennai, India
- Overview: A congress providing a platform for in-depth discussions on the future of the global seafood industry, focusing on safety, equity, and sustainability in trade.
- Website: https://wsc2026.com/?utm_source=chatgpt.com

Aquaculture America 2026

- Dates: February 16–19, 2026
- Location: Paris Las Vegas Hotel, Las Vegas, Nevada, USA
- Overview: The premier national aquaculture conference in the U.S., featuring a comprehensive trade show, technical sessions, and networking opportunities.
- Website: https://was.org/meeting/code/AA2026?utm_source=chatgpt.com

Aquaculture Horizons 2026

- Dates: April 13–15, 2026
- Location: Singapore
- Overview: An international conference and exhibition focusing on the latest advancements in aquaculture and seafood, offering a platform for experts and industry leaders to exchange insights.
- Website: https://www.theaquacultureconference.com/?utm_source=chatgpt.com

Seafood Expo Global 2026

- Dates: April 21–23, 2026
- Location: Fira Barcelona Gran Via, Barcelona, Spain
- Overview: The world's largest seafood trade event, offering over 20 educational sessions and a vast exhibition space covering all sectors of the seafood industry.
- Website: https://www.seafoodexpo.com/global/?utm_source=chatgpt.com

World Aquaculture, Fisheries and Seafood Conference (WAC 2026)

- Dates: June 25–27, 2026
- Location: Hybrid event in Barcelona, Spain
- Overview: A global platform for discussing the latest in aquaculture science, sustainability, and policy, combining in-person and online participation.
- Website: https://www.worldaquacultureconference.com/information/welcome-message?utm_source=chatgpt.com

Nor-Fishing Exhibition 2026

- Dates: August 18–20, 2026
- Location: Trondheim Spektrum, Trondheim, Norway
- Overview: A leading international trade fair for the fisheries industry, showcasing the latest technological solutions and industry advancements.

- Website: https://maritime-forum.ec.europa.eu/events/nor-fishing-exhibition-2026-2026-08-18_en?prefLang=hr&utm_source=chatgpt.com

News

U.S. FDA introduces new import requirements after radioactive contamination in Indonesian shrimp

The U.S. Food and Drug Administration (FDA) announced new import certification requirements for shrimp and certain spices from Indonesia following detection of Cesium-137 in a processed shrimp consignment. The measures (effective October 31, 2025) impose accredited third-party or government certifications for shipments from affected firms and regions, and keep listed firms under heightened scrutiny even after removal from the agency›s red list. This action has immediate trade and market-confidence implications for Indonesian shrimp exporters and their buyers.
Source: Reuters (Oct 4–5, 2025).

Indonesia's shrimp sector suffers price falls and lower processing after contamination scare

Following the contamination incident, Indonesia's shrimp processing and exports have suffered sharp declines: processing absorption in affected areas fell by roughly 30–35% and prices dropped in some local markets by up to ~35%. Though the issue originated from a single processor, buyer confidence across the supply chain has been shaken, prompting government task forces to investigate and industry calls for strengthened traceability and testing.
Source: Reuters (Oct 3, 2025).

NOAA identifies aquaculture opportunity areas off Texas coast

A federal NOAA study has identified approximately 4,500 acres off the Texas coast as promising Aquaculture Opportunity Areas (AOAs) suitable for sustainable offshore and nearshore farming (finfish, shellfish, seaweed, and multi-species systems). The designation is part of a broader U.S. policy push to boost domestic aquaculture, improve seafood security and reduce reliance on imports. The study highlights preferred sites near Port Mansfield, Matagorda Bay and southeast of Freeport, and stresses marine-spatial planning to reduce conflicts with fishing and vessel traffic.

Source: Houston Chronicle / NOAA (late Sept–Oct 2025).

Regional policy and capacity news — Morocco, Nova Scotia and beyond

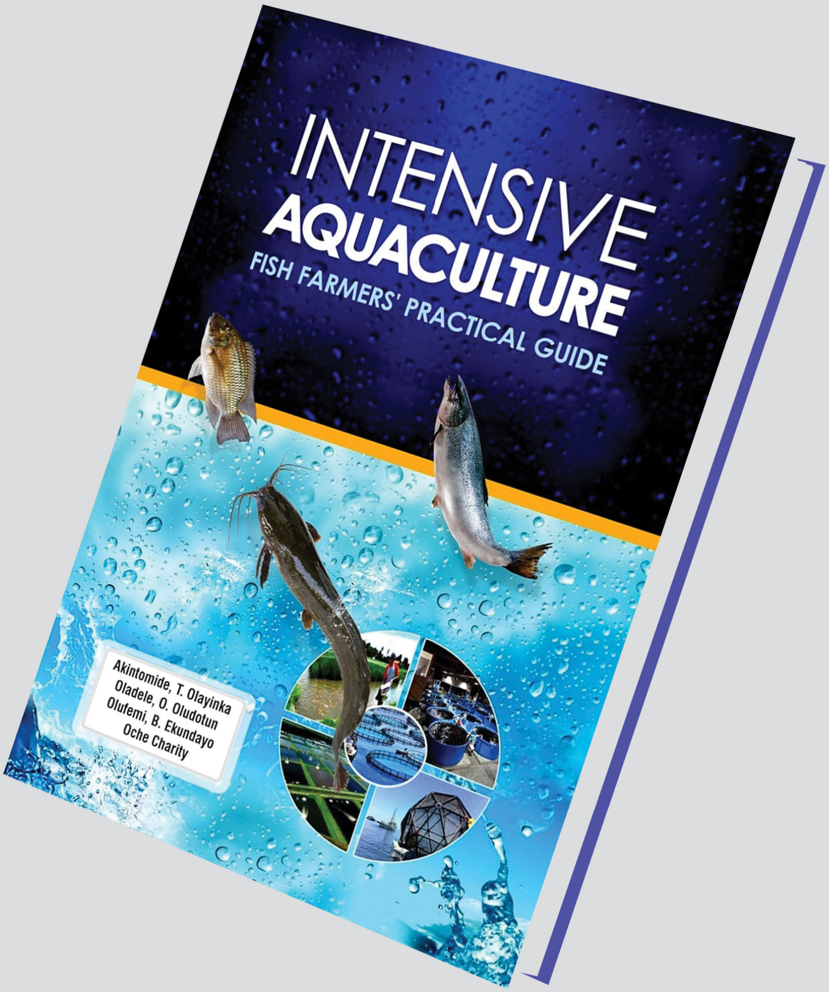
A World Bank strategic review (Sept 2025) highlights institutional and administrative barriers that limit Morocco's progress in marine aquaculture, urging reforms to unlock coastal job creation. Meanwhile, community opposition and regulatory hearings continue to shape salmon-farm expansion cases in Canada (Nova Scotia), and various industry events (e.g., FARM 2025 in Indonesia; Responsible Seafood and welfare workshops) signal active stakeholder dialogue on sustainability and welfare.

Sources: World Bank / Ecofin (Sept–Oct 2025); Ecojustice (Oct 3, 2025); FARM 2025 coverage (Oct 2025).

Russia eyes India as key market for seafood exports

Russia is increasingly looking to India as a strategic market for its seafood exports. With growing demand for high-quality seafood in India and strong trade relations between the two countries, Russian exporters see significant opportunities to expand their market share. Officials from the Russian seafood industry highlighted that India's rising middle class and changing consumption patterns are driving demand for fish and other marine products. Key Russian products expected to enter the Indian market include salmon, cod, and various shellfish, with an emphasis on sustainable and high-quality offerings. Industry analysts suggest that enhanced cooperation, trade agreements, and logistics improvements could further strengthen Russia's position in India. The move comes as Russia seeks to diversify its export markets amid global economic uncertainties and shifting international trade dynamics. Experts note that India's seafood import market has been growing steadily, making it an attractive destination for countries looking to increase their global footprint in the sector. Russian exporters plan to leverage competitive pricing, quality assurance, and promotional campaigns to capture Indian consumers' attention. This strategic shift underscores the broader trend of Russia expanding trade partnerships in Asia, with India emerging as a key player in the country's long-term seafood export strategy.

Book introduction



Title: **Intensive Aquaculture** (Fish Farmers' Practical Guide) – September 2024 Edition

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Publisher / Year:

E-book (PDF); original publication year: 2019, newly updated version issued September 2024

Length: Approximately 301 pages

Summary (Practical, Field-Oriented, Highly Applicable)

This guide is a well-illustrated, field-oriented manual that delivers hands-on instruction for fast, intensive fish production. It is especially suited for practitioners, students, agro-entrepreneurs, and extension professionals who need clear, actionable guidance.

Key content areas include:

Aquaculture Systems & Management: Types of culture systems, their design, operational functionality, and system management techniques.

Water Quality & Management: Practical methods for assessing culture water, maintaining water quality, and troubleshooting common water issues.

Hatchery Production & Management: Guidance on hatchery design, broodstock management, larval rearing, and early life-stage care.

Fish Nutrition, Feeding Technology & Feed Economics: Strategies for optimal feeding, technological tools for feed delivery, cost-benefit considerations.

Aquaculture Waste Management & Economics: Techniques for handling and reusing waste, economic assessments of waste control systems.

Fish Health Management: Prevention, diagnosis, and treatment of common aquaculture diseases; biosecurity protocols.

Production Analysis: Performance indicators, productivity tracking, yield optimization.

Products Marketing & Sales Strategies: Approaches to marketing fish products, sales planning, value-addition ideas.

Field-Related Q&A: Answers to common operational challenges encountered in the field, enabling troubleshooting.

Fit for:

o Aquaculture students, extension agents, and new entrants who want a practical grounding.

o Experienced farmers or managers looking to upgrade systems or optimize production.

o Educators/trainers seeking a ready-made manual for hands-on teaching.

o Agro-investors evaluating operational viability of fish farming ventures.

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Qsr Address:
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