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About Blue Spectrum

Blue Spectrum is the official quarterly magazine of the School of Fisheries, Centurion University of Technology and Management (CUTM), Paralakhemundi, Odisha, dedicated to promoting scientific communication, knowledge sharing, and innovation in Fisheries and Aquatic Sciences. Published four times a year, the magazine provides a platform for students, researchers, academicians, scientists, and fisheries professionals to share research findings, field experiences, technical insights, innovations, and emerging developments. Its broad scope covers aquaculture, fisheries resource management, aquatic biodiversity, biotechnology, fish processing and value addition, fisheries economics and extension, aquatic animal health, climate change, and sustainable aquatic ecosystems.

Launched in 2026, Blue Spectrum aims to bridge the gap between scientific research, education, and practical applications in the fisheries sector. The magazine encourages scientific writing and knowledge exchange while highlighting contemporary technologies and sustainable approaches, including artificial intelligence, smart aquaculture, advanced processing, traceability, biotechnology, and conservation. Through its multidisciplinary content and contributions from the fisheries community, Blue Spectrum seeks to foster a vibrant culture of scientific communication and contribute to the sustainable growth and advancement of Fisheries and Aquatic Sciences.

From the Desk of the Chief Editor

It gives me immense pleasure to present the inaugural issue of Blue Spectrum, the quarterly magazine of the School of Fisheries, Centurion University of Technology and Management (CUTM), Paralakhemundi. This magazine is envisioned as a vibrant platform for sharing knowledge, research, innovations, field experiences, and emerging perspectives across the diverse domains of Fisheries and Aquatic Sciences. As the fisheries sector continues to evolve through advances in aquaculture, biotechnology, fish processing, artificial intelligence, sustainability, and aquatic resource management, effective scientific communication has become increasingly important. Through Blue Spectrum, we aspire to connect students, researchers, academicians, professionals, and stakeholders, while encouraging young minds to explore, learn, and communicate their ideas with confidence. I sincerely appreciate the contributions of all authors, reviewers, editorial board members, faculty, students, and well-wishers who have supported this initiative and made the first issue possible. I hope Blue Spectrum will grow into a meaningful forum for scientific exchange and continue to inspire innovation and sustainable development in the fisheries and aquatic sciences sector.

Warm Regards,

Dr. Sambid Swain

Editor-in-chief

Blue Spectrum

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Bluetooth Meets Seafood: BLE Sensors Transforming Seafood Traceability

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ABSTRACT

Seafood is one of the most heavily traded and most fraud-prone food commodities in the world, moving through fishing vessels, processors, cold stores, distributors, and retailers before it reaches a consumer's plate. At every one of these handoffs, information about the product's origin, temperature history, and handling can be lost, altered, or falsified. This article examines how Bluetooth Low Energy (BLE) sensor technology is emerging as a practical, low-cost tool for closing these traceability gaps. Unlike static RFID tags that must be manually scanned, BLE sensors broadcast identity and environmental data continuously to any nearby smartphone or gateway, making it possible to reconstruct a near-continuous, item-level history of a seafood shipment's journey. Drawing on recent research in wireless sensor networks, cold-chain logistics, and blockchain-enabled food traceability, the article explains how BLE works, why it is well suited to the seafood cold chain, where it is already being deployed, and what challenges remain before it becomes a mainstream traceability tool. The discussion is aimed at a general audience, seafood industry professionals, supply chain managers, and technology-curious readers rather than specialists in wireless protocol design.

KEYWORDS

Bluetooth Low Energy (BLE); seafood traceability; cold chain monitoring; IoT sensors; food supply chain; blockchain; fisheries logistics

Introduction

A piece of shrimp on a supermarket shelf may have travelled through a dozen hands before it reached the customer: a fishing crew, an on-shore processor, a cold-store operator, a freight forwarder, a customs inspector, a distributor, and finally a retailer. Each of these steps is an opportunity for the product's story to become murky. Studies of the global seafood trade have repeatedly found that a significant share of seafood sold to consumers is mislabelled or cannot be reliably traced back to its point of catch, undermining both food safety oversight and consumer trust (Ferrari, 2023; Bhat et al., 2021). Illegal, unreported, and unregulated (IUU) fishing compounds the problem, since fraudulent paperwork can disguise the true origin of a catch as it moves through a fragmented, multi-party supply chain (Alabi & Mondragon, 2023).

Digital tools such as barcodes, RFID tags, GPS trackers, and increasingly blockchain ledgers have been proposed as solutions, and each has found a place in seafood logistics. But most of these tools share a common weakness: they only record information when someone actively scans a tag or logs a data point. Between those scans, a shipment's real condition is essentially invisible. Bluetooth Low Energy (BLE) sensors are gaining attention precisely because they remove this blind spot. A BLE-tagged crate of fish does not wait to be scanned; it continuously "shouts" its identity and sensor readings into the air, ready to be picked up by any compatible device that happens to be nearby (Surgere, 2024). That shift from occasional, deliberate scanning to continuous, passive sensing is what makes BLE a genuinely different proposition for seafood traceability, not just a cheaper version of RFID.

The Traceability Problem in Seafood Logistics

Seafood is unusually hard to trace for three

structural reasons. First, it is highly perishable; quality begins degrading from the moment of catch, and safety depends on maintaining a narrow temperature band throughout transport, processing, and storage. Second, the supply chain is fragmented across many independent actors like small-scale fishers, processors, exporters, and distributors who often keep records in incompatible formats or on paper. Third, seafood is frequently transformed along the way (filleted, frozen, repackaged, mixed with other catches), which breaks the simple one-to-one link between a "batch" and its original source.

Recent systematic reviews of digital traceability technologies in fish supply chains conclude that no single technology addresses every stage of this journey. Instead, the strongest systems combine several tools, sensors for real-time environmental data, RFID or barcodes for batch identity, and blockchain for tamper-resistant record-keeping layered on top of one another (Bhatt et al., 2025). Within that combination, BLE sensors are increasingly positioned as the "sensing" layer: the component that continuously captures what is actually happening to the product physically, as opposed to what a paper or digital record claims happened.

What BLE Sensors Actually Do?

Bluetooth Low Energy is a wireless communication standard built for devices that need to run for months or years on a small battery while sending small amounts of data frequently. Unlike classic Bluetooth, which was designed for high-bandwidth uses like audio streaming, BLE trades bandwidth for extremely low power draw, making it well suited to small sensor tags. Foundational engineering studies of the protocol have shown that, depending on how the connection parameters are configured, a BLE device powered by a small coin-cell battery can theoretically operate for

anywhere from a couple of days up to well over a decade, with a single master device able to communicate with thousands of peripheral sensors (Gomez, Oller, & Paradells, 2012).

In a seafood logistics context, a BLE sensor is typically a small, rugged tag attached to a crate, pallet, or shipping container. It carries one or more miniature sensors, most commonly temperature, but sometimes also humidity, light exposure, shock, or door-opening detection — along with a tiny radio chip. Rather than waiting for a handler to scan it with a dedicated reader, the tag periodically broadcasts an "advertisement" containing its identity and latest readings. Any BLE-capable device nearby a warehouse gateway, a delivery driver's smartphone, even another BLE tag acting as a relay can pick up that broadcast and forward it to a central database (Wiliot, 2025). Because reading a BLE tag requires no line-of-sight and no deliberate scanning action, data can accumulate throughout transport rather than only at fixed checkpoints.

Why This Matters for the Cold Chain

Temperature control is the single most important variable in seafood quality and safety. A short break in refrigeration— a truck door left open too long, a delayed transfer between cold stores can accelerate spoilage and create food-safety risk long before any visible sign of decay appears. Traditional monitoring approaches often rely on either a single logger placed somewhere in a container, which cannot capture variation between individual pallets, or manual temperature checks at scheduled intervals, which cannot catch a brief excursion that happens between checks.

BLE changes this in two ways. First, because tags are cheap and low-power, they can be attached at the individual pallet or even case level rather than just once per container, giving a much finer-grained picture of where a cold-chain break actually occurred. Second, because BLE tags broadcast continuously rather than only when

scanned, a temperature excursion is captured automatically by any gateway within range, rather than depending on a worker remembering to check a logger. Industry analyses of BLE-based cold-chain deployments note that this combination allows operators to demonstrate compliance at the level of an individual item, showing not just that a shipment arrived on time but that it stayed within safe temperature thresholds at every point along the route (Elain Innovation, 2025).

This item-level visibility is particularly valuable for seafood exporters trying to meet the documentation demands of importing countries and retailers, many of which increasingly require proof of cold-chain integrity, not just a final delivery confirmation, before a shipment can be accepted or certified.

BLE as Part of a Larger Traceability Architecture

BLE sensors rarely work alone. Recent reviews of digital fish-supply-chain traceability point to an emerging architecture in which BLE or similar wireless sensors form the data-capture layer, feeding information into a shared digital ledger, often blockchain-based, that other supply chain participants and, in some designs, consumers can query (Alabi & Mondragon, 2023; Ismail *et al.*, 2023). In this model, a BLE tag on a batch of tuna records its temperature history from the moment it leaves the vessel; that history is periodically uploaded to a blockchain ledger alongside catch location, processing dates, and chain-of-custody information, creating a record that is both continuous and difficult to tamper with after the fact.

This layered approach also helps address one of the seafood industry's persistent fraud problems: substitution, where a lower-value or illegally caught fish is relabeled and sold as a higher-value or legally caught species. A blockchain record alone cannot detect substitution if the underlying

data entering it is unreliable; sensor-verified, time-stamped location and condition data from BLE tags makes it considerably harder to insert fraudulent information into the chain without leaving inconsistencies that automated checks can flag (Rahman et al., 2021).

Real-World Momentum

The direction of travel is visible in how seafood and cold-chain logistics providers are already experimenting with BLE. Passive, battery-free BLE tags, sometimes described as an alternative to conventional UHF RFID, are being trialled specifically because they combine RFID-like low cost and simplicity with BLE's ability to be read by ordinary smartphones rather than specialized readers, lowering the barrier for smaller processors and distributors to participate in a shared traceability system (Bottani et al., 2025). Meanwhile, newer BLE standard versions have improved the accuracy of location-related features, which researchers suggest could soon make it possible to pinpoint not just that a temperature excursion occurred, but roughly where in a warehouse or vehicle it happened (Elain Innovation, 2025).

For an industry where a large share of processing and first-mile handling is done by small operators with limited IT budgets, the appeal of BLE is as much practical as technical: the readers are smartphones people already carry, the tags are inexpensive relative to active satellite trackers, and no specialized scanning infrastructure needs to be installed at every checkpoint for basic visibility to improve.

Challenges

BLE is not a complete solution on its own, and researchers are candid about its limitations. Range is short compared with cellular or satellite tracking, so BLE data collection depends on gateways or smartphones being physically present

along the route. A gap in coverage anywhere in the chain, such as during ocean transit or in a rural loading yard, means a corresponding gap in the record. Because BLE devices are designed to be easily discoverable, their transmissions can also be picked up by devices other than the intended reader; security researchers have documented weaknesses in how BLE's privacy features resist tracking by unauthorized parties, a concern that matters more as more valuable, item-level supply-chain data rides on the same broadcasts (Wu et al., 2024). Cost, while low per tag, still adds up across millions of shipped units, and battery-powered tags eventually need replacement or disposal, raising both maintenance and sustainability questions that battery-free designs are only beginning to address (Bottani et al., 2025).

There is also the broader systems challenge shared by every traceability technology: sensors can only be as trustworthy as the process for attaching them correctly and keeping them attached to the right batch. A perfectly accurate temperature log is of little value if a tag was swapped between crates, deliberately or by accident. This is precisely why current research increasingly treats BLE sensing as one verified input into a larger, cross-checked system rather than a stand-alone guarantee of traceability (Bhatt et al., 2025).

Future Scope

For all these open questions, the trajectory is clear. As BLE hardware gets cheaper and battery-free, energy-harvesting designs mature, tagging entire pallets or even individual high-value seafood items becomes economically realistic rather than a niche pilot project (Bottani et al., 2025). Combined with blockchain record-keeping and machine-learning-based anomaly detection approaches already being explored in academic fish-supply-chain research, BLE sensing is positioned to

become a standard, largely invisible layer of the seafood cold chain: quietly recording condition and location data at every step, surfacing problems in near real time, and giving buyers, regulators, and consumers a far more continuous and verifiable picture of where their seafood has actually been.

Conclusion

Seafood traceability has long been limited by the gaps between deliberate checkpoints, the moments when someone actually scans a tag or checks a temperature log. BLE sensors close those gaps by turning every nearby smartphone or gateway into a potential data collection point, generating a continuous, item-level record of a shipment's condition and movement rather than a handful of snapshots. Paired with blockchain ledgers and other digital traceability tools, this approach offers a practical path toward a seafood supply chain that is not just documented after the fact, but genuinely visible as it happens, a meaningful step toward tackling fraud, improving food safety, and rebuilding consumer trust in seafood, from ocean to plate.

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The Green Engines of the Future: Unlocking the Power of Microalgae

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ABSTRACT

Microalgae comprise a diverse group of photosynthetic microorganisms with significant ecological and biotechnological importance. Their high photosynthetic efficiency, rapid growth, carbon dioxide fixation capacity, and ability to synthesize proteins, lipids, pigments, antioxidants, and other bioactive metabolites make them promising resources for sustainable bioprocessing. The principal stages involved in microalgal cultivation and biotechnological utilization, encompassing strain collection, isolation, culture establishment, media formulation, strain selection, cultivation optimization, strain improvement, scale-up, harvesting, and downstream processing. Particular emphasis is given to the effects of key physicochemical and operational parameters, including light intensity and photoperiod, temperature, salinity, pH, carbon availability, nutrient supply, and mixing, on growth and biomass productivity. The potential of strain improvement approaches to enhance biomass yield, metabolite accumulation, environmental stress tolerance, culture stability, and harvesting characteristics is also discussed. Furthermore, the transition from laboratory-scale cultures to pilot- and industrial-scale production is examined, with emphasis on the technical constraints associated with light attenuation, temperature variability, gas transfer, nutrient gradients, hydrodynamic stress, and biological contamination. The major applications of microalgal biomass and metabolites in aquaculture, food and nutraceutical production, pharmaceuticals, cosmetics, biofuels, wastewater treatment, bioremediation, and carbon capture are highlighted. The integration of appropriate strain selection, controlled cultivation, strain improvement, scalable production systems, and efficient downstream processing is essential for improving the productivity and economic feasibility of microalgal biotechnology and for supporting its contribution to a sustainable bio economy.

KEYWORDS

Microalgae; Microalgal cultivation; bioactive compounds; strain selection; aquaculture

Introduction

Microalgae are microscopic photosynthetic organisms that inhabit a wide range of aquatic environments, including marine, freshwater, and brackish water ecosystems. They are often called the green engines of the Future. They are among the oldest life forms on Earth and contribute nearly 50% of the global oxygen production through photosynthesis. As primary producers, microalgae form the foundation of aquatic food webs by converting solar energy into organic matter that supports higher trophic levels. Owing to their rapid growth rates, efficient carbon dioxide fixation, and ability to synthesize a diverse range of valuable biomolecules, microalgae have emerged as one of the most promising biological resources for sustainable biotechnology. They are widely used in aquaculture, biofuel production, pharmaceuticals, nutraceuticals, cosmetics, agriculture, wastewater treatment, and carbon sequestration. Despite their enormous potential, successful commercialization requires careful attention to every stage of the production process, from field collection and laboratory cultivation to strain improvement and large-scale cultivation. Based on their major taxonomic and phylogenetic affinities, commercially relevant microalgae include representatives of Chlorophyta (Green algae), Bacillariophyta (Diatoms), Dinoflagellata, Haptophyta, Ochrophyta other stramenopiles, Rhodophyta and Euglenophyta, among others. Green microalgae such as *Chlorella*, *Scenedesmus*, *Tetraselmis* and *Dunaliella* (Fig.1) are important sources of biomass, pigments, proteins and other bioactive compounds. Diatoms, including

Chaetoceros, *Thalassiosira*, *Skeletonema* and *Phaeodactylum*, are particularly important in aquaculture because of their favourable nutritional profiles and production of essential polyunsaturated fatty acids. Haptophytes such as *Tisochrysis* and *Pavlova* are also widely used as live feeds in hatchery production. In addition, *Nannochloropsis*, a member of the stramenopiles lineage, has considerable commercial importance because of its high lipid content and value as an aquaculture feed organism. Cyanobacteria, although prokaryotic and taxonomically distinct from true eukaryotic microalgae, are commonly included in discussions of commercial microalgal biotechnology; *Arthrospira* spp., commercially marketed as “Spirulina,” are a prominent example. Thus, the commercial microalgal sector encompasses a phylogenetically diverse collection of organisms whose value is determined not only by their taxonomy but also by their growth characteristics, biochemical composition and suitability for specific applications.

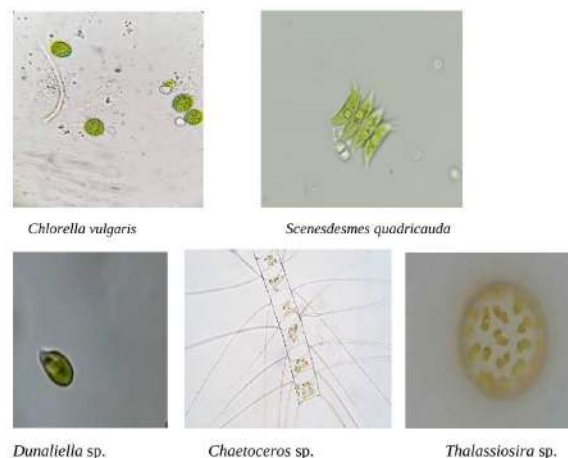


Figure 1. Microalgal Species used for Culture

Collection of Live Microalgae from Natural Environments

The collection of live microalgae from their natural habitats. The diversity of microalgae is immense, and different environments harbour species that possess unique physiological and biochemical characteristics. Marine coastal waters, estuaries, lagoons, mangrove ecosystems, freshwater lakes, reservoirs, rivers, aquaculture ponds, hypersaline environments, and even wastewater treatment facilities serve as valuable sources of microalgal biodiversity. Sampling is generally performed during periods of high biological productivity, when environmental conditions favour rapid algal growth.

Collection methods depend on the target species and habitat. Planktonic microalgae are commonly collected using plankton nets with mesh sizes ranging from 10 to 20 μm , while water samples can also be collected using Niskin bottles, Van Dorn samplers, or sterile sampling bottles. Benthic species are obtained by gently scraping rocks, sediments, submerged plants, or artificial substrates. During field sampling, researchers should record environmental variables such as water temperature, salinity, pH, dissolved oxygen, turbidity, nutrient concentrations, chlorophyll-a, and light intensity, as these parameters provide valuable information for recreating optimal laboratory culture conditions. To maintain cell viability, collected samples should be transported in clean, sterile, airtight containers under cool and shaded conditions. Excessive exposure to sunlight or high temperatures during

transportation should be avoided, as these conditions may reduce cell viability and alter the natural community composition (Fig.2).

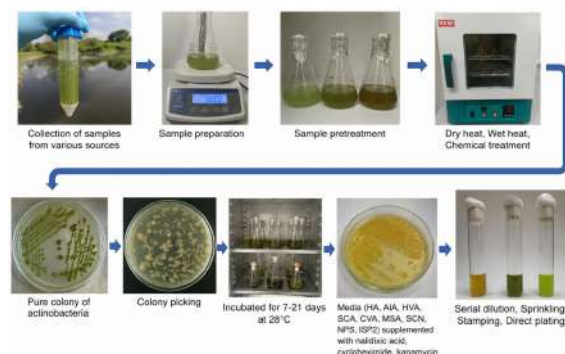


Figure 2. Sequential Steps in Microalgal Sampling, Isolation, and Pure Culture Development.

Laboratory Preparation for Microalgal Culture

A properly designed laboratory is essential for successful microalgal cultivation. Maintaining sterile conditions throughout the culture process minimizes contamination and ensures reproducible experimental results. Laboratory facilities should include a laminar airflow cabinet for aseptic manipulations, an autoclave for sterilization, incubators or controlled growth chambers, refrigerators for media storage, microscopes for routine observations, centrifuges, spectrophotometers, pH meters, conductivity meters, analytical balances, and air supply systems. All glassware, culture vessels, pipettes, and culture media should be sterilized before use. Glassware is usually sterilized by autoclaving at 121°C for 15–20 minutes under 15 psi pressure. Heat-sensitive solutions, including vitamins and certain antibiotics, are sterilized using membrane

filtration through 0.22 μm filters. The laboratory should maintain strict aseptic techniques, including disinfecting work surfaces, wearing gloves, and minimizing airborne contamination during inoculation. Proper environmental control is equally important. Culture rooms should maintain stable temperature, light intensity, and photoperiod while providing sufficient aeration and carbon dioxide to support photosynthesis and cell growth.

Culture Media and Chemicals Required for Microalgal Growth

Microalgae require a carefully balanced nutrient medium that supplies all essential elements needed for cellular growth and metabolism. These nutrients include macronutrients, micronutrients, trace metals, vitamins, and, for marine species, appropriate salt concentrations. Nitrogen is typically supplied as sodium nitrate, potassium nitrate, or ammonium salts, while phosphorus is provided as sodium or potassium phosphate. Diatoms additionally require dissolved silicate for frustule formation. Trace elements such as iron, manganese, zinc, copper, cobalt, and molybdenum function as enzyme cofactors involved in photosynthesis, respiration, and nutrient assimilation. Vitamins including thiamine (Vitamin B1), biotin (Vitamin B7), and cyanocobalamin (Vitamin B12) are required by many species for normal cellular metabolism. Several standardized culture media have been developed for different groups of microalgae. F/2 medium is widely used for marine phytoplankton, Conway medium is common in aquaculture hatcheries, Walne medium

supports mass production of live feeds, BG-11 is suitable for cyanobacteria, Bold's Basal Medium (BBM) is widely used for freshwater green algae, Chu-10 medium supports freshwater phytoplankton, and Zarrouk medium is specifically formulated for *Arthrospira* (*Spirulina*). The choice of medium depends on the nutritional requirements and intended application of the target species.

Isolation of Pure Microalgal Cultures

Natural water samples contain complex communities consisting of numerous algal species together with bacteria, fungi, protozoa, viruses, and small zooplankton. Therefore, obtaining pure cultures is essential before physiological, molecular, or biochemical studies can be performed. Isolation aims to separate a single algal species from mixed populations while minimizing contamination. Several isolation techniques are commonly employed depending on the characteristics of the target organism. Serial dilution reduces cell density until individual cells can be cultured separately. Micropipette isolation involves selecting a single cell or colony under an inverted microscope using a sterile glass micropipette (Fig.3). Agar plating techniques allow individual colonies to develop on solid nutrient media, facilitating isolation of pure strains. Flow cytometry and fluorescence-activated cell sorting (FACS) represent advanced approaches capable of rapidly isolating specific cells based on their fluorescence characteristics and size. Following isolation, cultures are repeatedly subculture under sterile conditions to

eliminate contaminating microorganisms. Regular microscopic examination and molecular verification help ensure that cultures remain axenic and genetically stable.

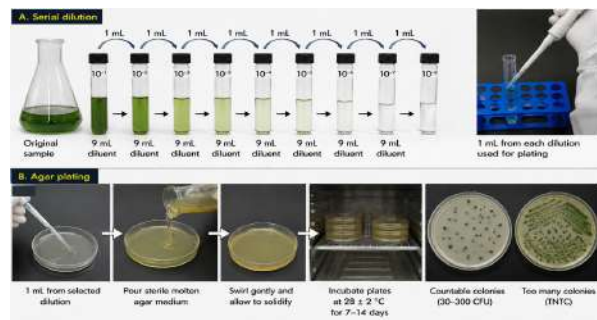


Figure 3. Isolation of Microalgae Using Serial Dilution and Agar Plating Techniques.

Environmental Factors Affecting Microalgal Growth

The growth and productivity of microalgae are strongly influenced by environmental conditions. Light is the primary energy source for photosynthesis, and both light intensity and photoperiod determine photosynthetic efficiency. Insufficient light limits growth, whereas excessive illumination may cause photo inhibition and oxidative stress. Temperature influences enzyme activity, membrane fluidity, and metabolic processes. Most commercially cultivated species grow optimally between 20°C and 30°C, although some polar or thermophilic species tolerate much broader temperature ranges.

Salinity regulates osmotic balance and varies considerably among freshwater, brackish, and marine species. Similarly, pH affects nutrient availability and enzyme function, with most species preferring values between 7.0 and 8.5. Carbon dioxide serves as

the primary carbon source for photosynthesis and is often supplied through aeration systems to enhance productivity. Proper mixing improves nutrient distribution, prevents sedimentation, facilitates gas exchange, and ensures that all cells receive adequate light exposure.

Selection of the Best Microalgal Strains

The selection of appropriate microalgal strains is one of the most critical decisions in any cultivation program. The ideal strain depends on the intended application, whether biomass production, lipid extraction, pigment synthesis, wastewater treatment, or aquaculture feed. An ideal commercial strain should exhibit rapid growth, high biomass productivity, efficient photosynthesis, elevated lipid or protein content, resistance to contamination, tolerance to environmental fluctuations, genetic stability, and ease of harvesting. Species capable of thriving under outdoor conditions with minimal nutrient requirements are generally preferred for industrial cultivation. Screening large numbers of naturally occurring isolates enables researchers to identify strains possessing superior physiological and biochemical characteristics.

Why Do We Need to Improve Microalgal Strains?

Microalgal strain improvement is essential to enhance the commercial viability and sustainability of large-scale microalgal cultivation. Although many naturally occurring microalgae possess valuable biochemical properties, wild strains often exhibit limitations such as slow growth, low

biomass yield, poor stress tolerance, and inconsistent metabolite production under industrial conditions. Improving microalgal strains helps achieve higher biomass productivity, enabling greater biomass production within shorter cultivation periods. It also promotes better product accumulation, increasing the yield of valuable compounds such as lipids, proteins, carbohydrates, pigments, antioxidants, and other bioactive metabolites. Enhanced strains are better adapted to high light intensities and fluctuating temperatures, allowing stable growth under outdoor cultivation conditions. Improved tolerance to high salinity, wastewater, and other environmental stresses enables the use of alternative water resources, reducing freshwater consumption and production costs. Strain improvement also enhances carbon dioxide utilization efficiency, resulting in increased photosynthetic performance, higher carbon sequestration, and improved biomass production. Furthermore, genetically stable strains exhibit greater culture stability, maintaining consistent productivity over extended cultivation periods. Increased resistance to contamination by competing microorganisms, bacteria, fungi, and grazers minimizes the risk of culture collapse and improves production reliability. Finally, improving cell characteristics that facilitate easier harvesting and dewatering reduces one of the most expensive steps in microalgal production, thereby lowering overall processing costs. Collectively, these improvements increase productivity, reduce operational costs, and support the successful commercialization of microalgae for applications in aquaculture, biofuels,

nutraceuticals, pharmaceuticals, wastewater treatment, and carbon capture.

Harvesting and Downstream Processing

Harvesting microalgal biomass represents one of the most energy-intensive and expensive stages of production. Since microalgae are extremely small and suspended in large volumes of water, efficient separation methods are required. Common harvesting techniques include centrifugation, membrane filtration, sedimentation, dissolved air flotation, and chemical or bio flocculation. After harvesting, biomass is washed, concentrated, and dried using spray drying, freeze drying, or solar drying depending on the intended application. Valuable compounds such as lipids, proteins, pigments, antioxidants, and bioactive molecules are subsequently extracted using physical, chemical, or enzymatic methods.

Technical Methods for Scaling Up Microalgal Cultivation

Successful industrial production requires gradual expansion from laboratory cultures to large-scale cultivation systems. Scale-up typically begins with agar plates and small flasks before progressing to larger culture vessels, carboys, bench-scale photobioreactors, pilot-scale reactors, and finally industrial production units. At each stage, inoculum quality must be maintained while minimizing contamination and physiological stress. Careful monitoring of cell density, nutrient concentrations, temperature, pH, dissolved oxygen, carbon dioxide supply, and light availability ensures healthy culture development throughout the scaling process.

Industrial cultivation may employ open raceway ponds or closed photo- bioreactors depending on species characteristics, production goals, environmental conditions, and economic considerations(Fig.4).



Figure. 4 Technical methods for scaling up microalgal cultivation

Why Do Promising Microalgae Perform Poorly at Industrial Scale?

Microalgal strains that exhibit excellent growth and productivity under controlled laboratory conditions often fail to perform similarly when cultivated at an industrial scale because scaling up does not eliminate biological weaknesses, it continuously exposes and amplifies them. In laboratory cultures, environmental conditions such as light, temperature, nutrient availability, and gas exchange are carefully controlled, whereas large-scale cultivation systems are subject to fluctuating environmental and operational conditions. As cultivation volume increases, light distribution becomes uneven due to self-shading, resulting in reduced photosynthetic efficiency. Temperature is no longer stable and varies with weather conditions, affecting cellular metabolism and growth. Gas transfer becomes a major

engineering challenge, with insufficient carbon dioxide delivery and oxygen accumulation limiting photosynthesis. Mixing, which is gentle in laboratory flasks, becomes more vigorous in large reactors, creating shear stress that can damage sensitive cells while still failing to distribute light and nutrients uniformly. Nutrient availability also becomes non-uniform because of concentration gradients and diffusion limitations, causing variations in growth and biomass composition. Furthermore, contamination is no longer an occasional risk but a continuous challenge, as industrial systems are constantly exposed to bacteria, fungi, protozoa, competing algae, and grazers that can rapidly reduce productivity or even cause complete culture collapse. Therefore, successful industrial-scale microalgal cultivation requires not only high-performing strains but also robust cultivation systems, efficient reactor design, precise environmental control, and effective contamination management to maintain consistent productivity.

Applications of Microalgae

Microalgae are emerging as versatile bioresources with applications across multiple sectors because of their ability to produce proteins, lipids, pigments, antioxidants and other high-value bioactive compounds. In aquaculture, they serve as essential live feeds for fish, shrimp, molluscs and zooplankton. In the food and nutraceutical industries, microalgal biomass provides proteins, vitamins, omega-3 fatty acids and natural pigments. Their bioactive metabolites are also being explored for pharmaceutical and

cosmetic applications, including antioxidant, antimicrobial, anti-inflammatory and skin-care products. Environmentally, microalgae contribute to wastewater treatment, nutrient recovery, carbon capture and bioremediation (Fig.5). They are also being investigated as renewable feedstocks for biofuels and other bioproducts, positioning microalgae as important contributors to the emerging circular and low-carbon bioeconomy.



Figure 5. Diverse Applications of Microalgae across Industrial and Environmental Sectors.

Conclusion

Microalgae are emerging as powerful biological resources for a sustainable and

low-carbon bioeconomy, with applications spanning aquaculture, food, nutraceuticals, biofuels and environmental management. Unlocking their full commercial potential requires a complete pipeline from strain discovery and selection to cultivation, strain improvement, scale-up and efficient downstream processing. Despite challenges such as contamination, environmental fluctuations and high harvesting costs, advances in biotechnology and bioprocess engineering are accelerating their industrial development. The future of microalgal biotechnology lies in robust strains, efficient production systems and high-value bioproducts, transforming microscopic organisms into major drivers of sustainable innovation.

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Smart Non-Thermal Fish Processing: Integration of Pulsed Electric Field, Cold Plasma and Artificial Intelligence for Sustainable Seafood Preservation

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ABSTRACT

Fish is a highly nutritious food and an important source of high-quality protein, omega-3 fatty acids, vitamins, and minerals. However, its high moisture content, water activity, endogenous enzymes, and unsaturated lipids make it highly susceptible to microbial spoilage, enzymatic deterioration, and lipid oxidation. Conventional preservation methods such as freezing, salting, smoking, drying, and thermal processing can extend shelf life but may affect texture, color, flavor, nutritional quality, and energy consumption. Emerging non-thermal technologies such as pulsed electric field (PEF), cold atmospheric plasma (CAP), and high-pressure processing (HPP) offer promising alternatives for seafood preservation. This article proposes an innovative concept of artificial-intelligence-integrated multi-hurdle non-thermal fish processing, combining PEF, cold plasma, HPP, smart sensors, artificial intelligence (AI), intelligent packaging, and cold-chain monitoring. PEF can support microbial control, salting, drying, and extraction, while AI can optimize processing conditions according to fish quality. The proposed system could improve safety, quality, shelf life, resource utilization, and sustainability in the seafood industry.

KEYWORDS

Fish processing, pulsed electric field, cold plasma, artificial intelligence, non-thermal processing, high-pressure processing, smart seafood

INTRODUCTION

Fish is highly perishable because its high moisture content, nutrients, endogenous enzymes, and unsaturated fatty acids provide favorable conditions for microbial growth, enzymatic reactions, and lipid oxidation. These processes rapidly reduce freshness, sensory quality, nutritional value, and economic value (Kumar et al., 2026; Peng et al., 2025). Traditional preservation methods include icing, refrigeration, freezing, salting, smoking, drying, fermentation, and canning. Although effective, some methods can cause undesirable changes in texture, color, flavor, nutrients, and energy efficiency. Increasing consumer demand for fresh-like, minimally processed, safe, and sustainable seafood has encouraged research into non-thermal processing technologies (Rathod et al., 2022). PEF, CAP, and HPP can provide microbial control with reduced thermal exposure. Among these technologies, PEF is particularly promising because electrical pulses can cause electroporation of biological membranes, influencing microbial inactivation and mass transfer (Kumar et al., 2026). The integration of such technologies with AI and real-time sensors could transform conventional fish processing into precision processing, in which treatment conditions are selected according to the characteristics of each fish batch (Peng et al., 2025).

PULSED ELECTRIC FIELD TECHNOLOGY

PEF involves exposing fish or other biological materials to short-duration, high-voltage electrical pulses. Electroporation can increase membrane permeability and contribute to microbial inactivation and mass transfer (Kumar et al., 2026).

Microbial Control

Microbial contamination is a major cause of fish spoilage. PEF can contribute to microbial reduction without intensive heating. Its effectiveness depends on electric-field strength, pulse duration, number of pulses, temperature, food composition, and microorganism characteristics (Kumar et al., 2026). Therefore, PEF is most appropriately used as one hurdle in a multi-hurdle preservation system rather than as a universal replacement for conventional processing.

Salting, Marination and Drying

Electroporation can increase tissue permeability and facilitate the movement of salt, water, and marinade components into fish tissue. PEF may therefore improve the efficiency and uniformity of salting and marination (Kumar et al., 2026).

PEF pretreatment can also enhance mass transfer during drying, potentially reducing drying time and improving process efficiency. In addition, PEF can assist the extraction of valuable compounds from fish-processing residues, contributing to by-product utilization (Kumar et al., 2026).

COLD ATMOSPHERIC PLASMA

Cold atmospheric plasma is generated by energizing a gas and producing reactive species capable of damaging microorganisms. Because it can operate at relatively low temperatures, CAP has potential for surface decontamination of fresh and minimally processed seafood (Rathod et al., 2022; Russo et al., 2024). The major advantages of CAP include low-temperature operation, rapid treatment, and potential reduction in dependence on conventional chemical sanitizers. However, excessive plasma exposure can promote lipid oxidation. This is particularly

important in fish because polyunsaturated fatty acids are highly susceptible to oxidation (Russo et al., 2024). Therefore, the treatment should use the minimum effective intensity necessary to achieve the required microbial reduction.

HIGH-PRESSURE PROCESSING

HPP uses high hydrostatic pressure to reduce microorganisms while limiting conventional heat exposure. It has potential applications in packaged fish, shellfish, ready-to-eat seafood, and other high-value products (Rathod et al., 2022).

HPP can contribute to shelf-life extension while maintaining many fresh-like properties. However, pressure can influence texture and color, and HPP equipment requires substantial capital investment. Therefore, HPP should be used selectively as an additional hurdle in an integrated preservation system.

ARTIFICIAL INTELLIGENCE IN FISH PROCESSING

AI could become the decision-making component of future fish-processing plants. Sensors could measure temperature, pH, color, firmness, moisture, electrical conductivity, freshness indicators, and temperature history. Computer vision could identify size, shape, discoloration, bruising, and physical damage.

These data could produce a digital quality profile for each batch. AI could then recommend appropriate processing conditions within scientifically validated safety limits.

A simplified system could operate as:

Fish quality assessment → AI prediction → PEF treatment → CAP/HPP → quality verification → smart packaging

Recent research has identified AI integration, improved equipment, process

optimization, and cold-chain management as important future directions for electric-field technologies in fish processing (Peng et al., 2025).

SMART PACKAGING AND COLD-CHAIN MONITORING

Fish quality can continue to deteriorate after processing because of temperature fluctuations, oxygen exposure, and microbial activity. Smart packaging could monitor temperature, oxygen exposure, package integrity, and freshness-related indicators.

Connecting these data with digital traceability systems could allow processors and retailers to monitor actual storage conditions. In the future, this may support dynamic shelf-life prediction, where remaining shelf life is estimated using real-time product and temperature information rather than relying only on a fixed expiry date.

CIRCULAR FISH PROCESSING

Fish-processing plants generate heads, skins, bones, scales, frames, and viscera. These residues contain proteins, collagen, gelatin, lipids, minerals, peptides, and other valuable compounds.

PEF can improve mass transfer and support extraction of useful components from marine biomass (Kumar et al., 2026). Thus, future facilities could operate as marine biorefineries:

Fish → premium fillets → non-thermal preservation

By-products → PEF-assisted extraction → collagen, gelatin, protein products and valuable lipids

This approach can reduce waste and increase the economic value of fish resources.

INTEGRATED PROCESSING MODEL

The proposed smart fish-processing system consists of the following stages:

1. **Smart reception:** Sensors and computer vision assess incoming fish.
2. **AI classification:** Freshness, size, quality, and microbial risk are evaluated.
3. **PEF treatment:** A validated PEF condition is selected.
4. **Multi-hurdle preservation:** CAP, HPP, refrigeration, drying, or salting may be applied.
5. **AI endpoint detection:** Sensors monitor processing conditions and quality.
6. **Smart packaging:** Product and storage information are recorded.
7. **Intelligent cold chain:** Transportation and storage conditions are monitored.
8. **By-product valorization:** Processing residues are converted into value-added products.

The complete concept can be summarized as:

Sense → Predict → Process → Verify → Package → Monitor → Valorize.

ADVANTAGES AND CHALLENGES

The proposed system could provide several advantages. Non-thermal technologies can improve microbial control while reducing some quality changes associated with intensive thermal processing (Rathod et al., 2022). PEF provides multiple applications, including microbial control, salting, drying, and extraction (Kumar et al., 2026). AI could reduce unnecessary processing by selecting conditions according to product characteristics. Smart packaging and cold-chain monitoring could further reduce food losses.

However, several challenges remain. These include high equipment costs, industrial scale-up, treatment uniformity, oxidation,

process standardization, regulatory validation, and consumer acceptance. Kumar et al. (2026) also highlighted the need for further development of PEF equipment, optimization of processing conditions, and industrial application.

CONCLUSION

The future of fish processing requires technologies that can simultaneously improve food safety, shelf life, sensory quality, nutritional retention, sustainability, and economic efficiency. PEF, cold plasma, and HPP have considerable potential for achieving these objectives (Rathod et al., 2022; Russo et al., 2024). PEF is especially promising because of its multifunctional applications in microbial control, mass transfer, salting, drying, and extraction. Kumar et al. (2026) demonstrated its potential specifically for fish preservation and highlighted opportunities for combining PEF with other emerging technologies. The integration of PEF and other non-thermal technologies with AI represents an important future direction. AI-enabled systems could assess fish quality, optimize processing conditions, monitor processing endpoints, and support shelf-life prediction. When combined with smart packaging and intelligent cold-chain management, this approach could reduce food loss and improve seafood traceability.

Although scale-up, cost, oxidation, standardization, regulation, and consumer acceptance remain important challenges, AI-integrated multi-hurdle non-thermal processing could represent a new paradigm in fish-processing technology, moving the industry toward precision, intelligent, sustainable, and circular seafood processing.

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Applications of Nutraceuticals in Aquaculture: Improvement in Growth, Immunity and Disease Management

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ABSTRACT

Nutraceuticals are promising functional feed additives in aquaculture, providing natural approaches to improve growth, feed utilization, immunity, stress tolerance, and disease management. Derived from terrestrial and marine sources, they include amino acids, fatty acids, nucleotides, vitamins, minerals, polysaccharides, herbal extracts, probiotics, prebiotics, organic acids, and exogenous enzymes. Their use is increasing as sustainable alternatives to antibiotics and therapeutic chemicals, whose excessive application can contribute to antimicrobial resistance and environmental residues. Nutraceuticals enhance performance through antioxidant defense, non-specific immunity, gut microbiota modulation, improved nutrient digestibility, and stress reduction. Immunostimulants such as β -glucans and chitin enhance disease resistance, while probiotics, prebiotics, and synbiotics promote intestinal health. Exogenous enzymes improve plant-feed digestibility, and dietary administration offers a practical delivery method, although nanodelivery may enhance targeted delivery. Despite their potential, further research is needed on species-specific doses, synergistic interactions, mechanisms, delivery, and regulation. Overall, nutraceuticals support healthier, productive, and sustainable aquaculture.

KEYWORDS

Nutraceuticals, Aquaculture nutrition, Immunity, Stress mitigation, Disease management

Introduction

Hippocrates, roughly 2500 years ago, originally proposed the concept of using appropriate foods for health and medicinal purposes. Dr. Stephen D. Felice defined "nutraceuticals" in 1989 as a food or substance that provides health and therapeutic benefits, such as illness prevention and therapy (Kalra, 2003). Nutraceuticals include nutrient-dense foods like Spirulina and garlic, as well as particular chemicals such as vitamins, lycopene, and omega-3 fatty acids. Gupta et al. (2010) report difficulty distinguishing between food, nutraceuticals, dietary supplements, functional foods, and medications. This approach was previously acknowledged for improving human health, but has recently gained prominence in animal feeding. Natural food products from both terrestrial and marine sources provide significant medicinal benefits. Nutraceuticals refer to goods produced from both terrestrial and marine sources, including isolated nutrients, nutritional supplements, genetically altered foods, herbal items, processed foods, and beverages.

Types of Nutraceuticals

On the basis of bio-functional properties of bioactive compounds derived from both terrestrial and marine sources can be classified as follows:

Dietary Supplements

According to (Food and Administration, 1995) USA, dietary supplements are considered those preparations which are made up of "dietary constituents taken orally in order to supplement the nutritional requirements of diet." Dietary constituents mean bioactive compounds like amino acids, vitamins, minerals, fibers, metabolites and some enzymes. Dietary

supplements also include extracts in functional food is considered as a usual food that includes one or more ingredients that have a therapeutic effect and nutritional benefits (Jalili et al., 2001). In contrast, in Japan functional foods include certain criteria as (1) functional food is taken from natural sources and should be taken in their natural form rather than being processed into various dosage forms such as tablets, capsules or powder; (2) should be taken regularly as part of the normal daily diet, and (3) they work both ways to prevent disease and treat them (Arai, 1996).

Medicinal Food

The medicinal food is specially formulated food products that are recommended for consumption under the supervision of a doctor, aimed at managing a certain disease through the diet with specific nutrient requirements that can be obtained only via special formulation rather than regular diet. Dietary supplements or functional foods do not fall into this category (Radhika et al., 2011).

Role of nutraceuticals in aquaculture

Use of nutraceuticals has been widely encouraged for improved production performance, growth promotion, increased immunity, and feed utilization efficiency (Sinha et al., 2007; Tejpal et al., 2021). Different categories of nutraceuticals currently used in the aquafeed industry and farms include enzymes, methyl donors, immunostimulatory chitin and chitosan, extracts of polychaete and tunicates, vitamins, antioxidants, minerals, amino acids, growth hormones, organic acids, carotenoids, and so forth. Nutraceuticals have been seen as less worrisome in the aquafeed industry as they are likely to yield positive results in relation to feed utilization, immunity,

meat quality, stress tolerance, reproductive and productive performance, and improved water quality in culture through reduced feed wastage and better feed utilization. The lack of growth in the output of marine products along with the increase in demand for the product led to the need for improvement in aquaculture production. Land and water limitation causes the inland farming system to be more intensive, hence more likely to have diseases because of stress, reducing the immunity of the fishes. There are several pathogens in the aquatic ecosystem that wait for a chance to affect the fishes. Several outbreaks of diseases in aqua farms have been witnessed in recent times. To prevent diseases from happening in aquaculture, the application of antibiotics and drugs has become popular. The uncontrolled use of these chemicals leads to antibiotic resistance, buildup of residues in the aquatic ecosystems, and other negative impacts. Some studies suggest that nutraceuticals possess the capacity of stimulating growth and boosting immunity of fishes.

The studies show that nutraceuticals can promote an increase in feed consumption in fish; provide anti-stress and antimicrobial capabilities and stimulate maturation without causing any negative effects. In addition, some types of feed additives in aquaculture may also be considered as nutraceuticals (Brower, 1998). There are numerous causes behind stress for fish living in aquaculture environment. High stocking density, changes in climatic conditions, exposure to pesticide or insecticides, malnutrition, utilization of plant products with anti-nutritional factors may cause stress for fish in an aquaculture environment. However, today many scientists have developed various compounds that may be able to mitigate stress in fish. Such compounds can be classified based

on their functions and chemical composition. Some common nutraceuticals used in aquaculture include:

Traditional

The ancient cultures such as Indian, Chinese, Egyptians, and Sumerians have been quite aware about the significance of foods as medicines and these facts have been documented in their epics and other such documents. As an instance, the ancient Indian medical science Ayurveda has clearly indicated about the significance of food as medicines. The traditionally utilized simple and natural foods are regarded as traditional nutraceuticals, while commercially available products having additional nutrients through breeding or hybridization techniques are considered as nutraceuticals.

Based on the chemical nature

Amino acids and peptides

Essential Amino Acids (EAA)

Some amino acids can serve as essential nutrients as well as stress-reducing agents while peptides can act as antimicrobial agents. Many important AAs such as tryptophan, pyridoxine, tyrosine, glycine, and arginine have been known to reduce stress effect. For example, tryptophan is a very important AA which is used in the synthesis of serotonin (5-HT). Serotonin has an important role to play in reducing stress in fish species (Hoseini et al., 2019). Several studies have shown that tryptophan has the ability to reduce the stress effect in rainbow trout (Lepage et al., 2002), rohu (Akhtar & Abdullah, 2021) (Kumar et al., 2014), mrigal (Tejpal et al., 2009) and juvenile grouper (Höglund et al., 2007). Laboratory studies conducted by FNBP in ICAR-CIFE

have shown that tryptophan (1.36%) significantly reduces the stress effect (Akhtar et al., 2013). Tyrosine, as the precursor of catecholamines, works similarly to noradrenalines and reduces the stress in fishes. Besides, glycine and arginine are the other important AAs which help the immune system and antioxidants of the fish. In addition, glycine, an amino acid, has an important role to play in osmoregulation while the survival of oysters transferred from freshwater to seawater increases with the supplementation of glycine (Takeuchi, 2007).

Fatty acids

Polyunsaturated fatty acids (PUFA) which are a part of the n-3 and n-6 group of fatty acids act as precursors of eicosanoids, which are biologically active substances (Bakhle, 1983). According to JOLLY, 1999, n3 PUFA increased the immunity of rohu fingerlings. But according to (Fontana et al., 1999), the diet containing PUFA at a concentration of 3% inhibits immunity in juveniles.

Nucleotides

Supplementation with nucleotides in diet increases immunity in fishes (Beale et al., 1999; Snyderman et al., 1999). Studies have revealed that supplementation with nucleotides in diet in salmon increases the overall health of fish (JOLLY, 1999; Sukumar et al., 1999). Besides, Pepin et al. (1999) have concluded that inclusion of RNA in diet increases survival of fish.

Vitamins

Vitamins are the primary micronutrients that are needed in small amounts for various functions in the animals. Vitamins A, C, and E play significant roles in antioxidant activities and

fish immunity. A high concentration of ascorbic acid (3000 mg/kg diet) enhances immune activity and complements function (Soliman, 1985). Chen et al. (2004) reported that addition of vitamin C in more than 100 mg/Kg in fish diets enhanced immunity. Supplementing vitamin E reduced nitrite stress in rohu (Ciji et al., 2012), whereas in channel catfish, vitamin E supplementation improved immunological activity (Zhu et al., 2012). Vitamin A and Beta Carotene are strong antioxidants in biological systems; astaxanthin administration showed an immunomodulatory effect in rainbow trout (Thompson et al., 1995). Pyridoxine, commonly known as Vitamin B6, plays an effective role in reducing stress due to increased levels of serotonin and GABA. A dose standardization study conducted in our laboratory revealed that addition of 100 mg/kg of pyridoxine proved effective for stress management and improved growth performance (Akhtar et al., 2013). Pantothenic acid reduces the cortisol release and manages stress.

Minerals

Minerals are inorganic nutrients that can serve as anti-stress agents. Mineral supplementation, both organic and inorganic, can effectively reduce stress in fish. Supplementation with zinc picolinate reduced oxidative stress in rainbow trout (Kucukbay et al., 2006). According to Rider et al. (2009), organic selenium in the diet can lower oxidative stress in grouper fish.

Polysaccharides

Polysaccharides primarily target the non-specific immune systems of aquatic animals. Many polysaccharides, including microbial levan, beta glucan, chitin, lactoferrin, and inulin, have been employed as immune-stimulants in recent years. β -glucans are glucose polymers having a backbone of β -(1-3)

connected β -glucose. D-glucopyranosyl units. It can attach to several cellular receptors and activate them. Zhang et al. (2014) found that β -glucan improved fish resistance to bacterial and viral diseases.

Herbal extracts

Herbal extracts are compounds capable of neutralizing reactive oxygen species and boosting the immune systems of animals. Various plant extracts exhibit immune-enhancing and stress-reducing effects in fish (Harikrishnan et al., 2011; Serradell et al., 2020). Bioactive substances like Rutin (Toonasinensis) have been identified as potent antioxidants and anti-stress bioflavonoids, proving effective for crustaceans. A laboratory study on guava and mango leaf extracts demonstrated that a 0.5% inclusion of either guava or mango leaf extract in the diet improves immunity in *Labeo rohita* fingerlings (Fawole et al., 2016).

Based on the functions

Anti-stress & antioxidant nutraceuticals

This category is constituted by most of the vitamins, minerals, and herb extracts. Supplementation with bovine lactoferrin in an amount of 1200 mg/kg of feed in the groupers decreased salinity stress (Saichiro et al., 2006). The herbs *Astragalus membranaceus* and *Astragalus paniculatus* have proved to be stress relieving in the case of *Cyprinus carpio* and tilapia fish (Wu et al., 2007).

Immunostimulants

The immune system of fish and shellfish is not as complex as that of the terrestrial animals, and most often the main emphasis is placed on the non-specific immune system. A number of polysaccharides and oligosaccharides enhance

the non-specific immunity in fish and shellfish. It was observed that addition of 5 mg/kg of levamisole in the feeds of carp fish enhanced their phagocytosis. (Boonyaratpalin and New, 1995) found that black tiger shrimps were more tolerant to dissolved oxygen and had enhanced immunity with the administration of peptidoglycan. Also, beta-glucan showed better resistance against bacteria and viruses in crustaceans (Misra et al., 2006). Addition of 1% Microbial Levan was found to enhance the immune status of young rohu fish along with inulin. A few plant extracts such as saponin, tannin, glycyrrhizin, and azadirachtin improve the immune system of fish and shellfish.

Antimicrobial and viral nutraceuticals

Antimicrobial properties are possessed by many nutraceuticals such as onion, garlic, thioles, sulphides, terpenes such as oregano, turmeric, and ginger, phenolic such as cloves, nutmeg, cinnamic acid, glycosides such as sugar, citral, citronellol, esters and alcohols. At present, most aquaculture applications are in their experimental stages. Extracts from plants and immunostimulants such as glucan, chitin, lactoferrin, levamisole have antimicrobial properties.

Growth promoters

Various natural substances and minerals enhance the growth of fish. As per Abdel-Tawwab et al. (2008), addition of spirulina enhances the growth of tilapia. Spirulina, rich in carotenoid and phenolic substance, has been reported to enhance development and phosphatase activity in rohu under metallic stress (James, 2010). Extracts from yeast and seaweed enhance the growth of fishes. Growth enhancing herbs have been reported to enhance the process of transcription, hence increasing the growth rate. As per Chitra (1995),

enrichment of artemia nauplii with herbs like stressol I & II enhance the growth of *Penaeus indicus*.

Acidifiers

Organic acids, either singularly or in mixture, can serve to improve digestion, gut microflora, and general health. These are also referred to as acidifiers. Incorporation of acidifiers in the diet enhances the longevity of the feed, helps in digestion by enzyme activity and acts as an intermediate in the TCA cycle. In our laboratory, we observed that when citric acid (3%) and exogenous phytase were used in mixture, their efficiency was increased in rohu (Baruah et al., 2007). Some other acidifiers commonly used in animal diets include formic acid and acetic acid. The mechanism of action of organic acids is as follows:

Prebiotics, probiotics and synbiotics

The probiotics are defined as microorganisms that enhance the properties of the resident flora on being used in humans and animals (Havenaar, 1992). The prebiotics are the non-digestible components of food which stimulate growth and development of the gut microflora. The synbiotics refer to the simultaneous use of the prebiotics and probiotics to create synergy. The common carp (Staykov et al., 2007). The probiotics reduce the bacterial infections and stimulate the production of immune-stimulating metabolites. Some of the probiotics commonly used in aquaculture are *Lactobacillus*, *Enterococcus*, *Bifidobacterium*, *Bacillus*, and *Streptococcus*. The prebiotics used in aquaculture systems include Mannan oligosaccharides (MOS), Xylan oligosaccharides (XOS) and Fructan oligosaccharides (FOS). Studies have indicated that use of the MOS in the fishes improves survival, immunity, and growth in rainbow trout

(Staykov et al., 2007), channel catfish (Welker et al., 2007), and common carp (Staykov et al., 2007).

Nutrizymes/exogenous enzymes

Nutrizymes are extracellular enzymes used as nutraceuticals which increase digestibility and growth. Additives in the plant feed usually include antinutritive factors and cellulose. This leads to digestive problems in fish and calls for more enzymes to counteract the adverse effects. Digestive enzymes like lipase, cellulase, protease, glucanase, phytase, and microbial amylase increase the digestibility in fish that are being fed on plant-based feed. It has been shown that gluconase increases digestibility of proteins in soy beans by 74-95% while phytase increases mineral and protein utilization through complexation with phytic acid (Coon 1998). Exogenous chitinase aids in improving the digestibility of chitin compounds in the diet. Addition of exogenous carbohydrate increases the glucose uptake in carnivores. It has been found that addition of non-gelatinized maize and microbial α -amylase in the diet of *L. rohita* fingerlings at lower than optimal protein level increased their growth and size.

Mode of delivery

Nutraceuticals can be administered through many routes, including parental, oral, and dietary supplements. A study on nucleotides found that oral yeast RNA supplementation improved phagocytic activity in common carp (Sakai et al., 2001), while high dietary RNA supplementation impacted the development and protein accretion of European seabass (Peres and Oliva-Teles, 1999). Injecting chitin improved fish immunological function. Research suggests that dietary supplementation in a safe manner is more cost-effective and efficient. Nutraceutical nanodelivery is an

emerging field that requires further research. Also, Nano delivery technologies offer advantages such as focused tissue delivery, reduced micronutrient loss, and cost reduction.

Future scope

Several forms of disease outbreaks in shrimp and fish farms have occurred in recent years, including WSSV and EMS, resulting in the loss of a huge volume of crops worldwide. This occurred mostly as a result of the fish's lower immunological condition. Although various publications have been published, there is still room for research on species-specific dose standardization and effective delivery methods. The field of nutraceuticals in aquafeed is still in its early stages, requiring control and regulatory measures similar to those for pharmaceutical products. Further research is needed to determine the effectiveness of nutraceuticals in aquafeeds, including species-specific dose standardization, synergistic effects, nanodelivery technologies, and mechanisms of action.

Conclusion

Fisheries and aquaculture can contain a variety of nutraceuticals. Antioxidants, for example, help to protect fish against the detrimental effects of free radicals, which can cause cell and tissue damage. They can also aid to boost the immune system and avoid illness. Methyl donors are important substances that aid in the synthesis of DNA and RNA. They are also necessary for the metabolism of lipids and proteins. Immunostimulants strengthen the immune system, making fish more resistant to disease. They can also assist to alleviate the severity of illnesses. Probiotics are living microorganisms that improve the gut health of fish. They can enhance nutrient absorption and prevent illness. Herbal extracts contain

chemicals that can improve fish health. Herbal extracts can enhance fish flavor, alleviate stress, and promote development. Although the use of nutraceuticals in aquaculture is still in its early stages, there is increasing evidence that they can improve fish health and production. More research is needed to discover appropriate nutraceutical doses and combinations for various fish species.

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From the Titanic to Fish Farms: The Journey of *Halomonas titanicae*

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ABSTRACT

The marine halophilic bacterium *Halomonas titanicae* was isolated from rusticles over the remains of the R.M.S. Titanic in 2010. This species has been extensively studied in the context of deep-sea iron biocorrosion and extreme environment adaptation. However recent research has uncovered the potential of this bacterium as a probiotic in aquaculture. Whole-genome analyses reveal that *H. Titanicae* possesses a range of osmoadaptation mechanisms oxidative stress response pathways, extracellular enzyme systems and biofilm-forming capabilities. The study also demonstrates that the gut-isolated strain *H. Titanicae* HT-Tc3 can improve the growth performance, digestive enzyme activity, antioxidant status, nonspecific immunity and resistance to *Aeromonassalmonicida* infection in turbot. These findings highlight the advantages of using marine probiotics over traditional terrestrial counterparts. Further research is needed to evaluate the safety, regulatory approval and commercial production of this promising aquafeed additive.

KEYWORDS

Halomonas titanicae; Probiotics; Aquaculture; Turbot

Introduction

Discovery of *Halomonas titanicae* from the RMS Titanic In 1912 the R.M.S. Titanic sank to the bottom of the Atlantic Ocean coming to rest 3,800 m below the surface. In 2010 while attempting to isolate bacteria from icicle-shaped rust formations ("rusticles") that had formed on the ships hull scientists were surprised to find a bacterium that they later named *Halomonas titanicae* (strain BH1).

Why Scientists Were Studying Shipwreck Bacteria

The scientists were interested in this bacteria because they wanted to know:

- How these bacteria could contribute to deep-sea bio-corrosion of submerged metals?
- What cellular mechanisms enable them to withstand the pressures and low temperatures of the deep sea?
- Could these organisms be harnessed to



recycle or recover metals from vessels?

Taxonomy & Characteristics

- *Domain: Bacteria*

- *Phylum: Pseudomonadota (Proteobacteria)*
- *Class: Gammaproteobacteria*
- *Order: Oceanospirillales*
- *Family: Halomonadaceae*
- *Genus: Halomonas*
- *Species: H. Titanicae*

General morphology:

It is a Gram negative, rod shaped and motile bacterium that commonly inhabits marine environments.

Salt Tolerance & Biofilm Formation

As a halophile *H. Titanicae* can tolerate and grow in a wide range of NaCl concentrations (0.5-25%). The bacterium produces amounts of Extracellular Polymeric Substances (EPS) enabling it to colonize marine surfaces and mucosal membranes by forming dense biofilms.

Role in Rusticle Formation

By catalyzing the oxidation of iron to insoluble ferric oxides (Fe_2O_3 , Fe_3O_4) *H. Titanicae* plays a prominent role in promoting deep-sea iron biocorrosion.

More Than a Corrosion Bacterium

Genomic Discoveries & Stress Tolerance

Genomic analysis of *H. Titanicae* reveals an abundance of genes that aid in regulation, heavy metal detoxification and ROS (Reactive Oxygen Species) scavenging.

Production of Beneficial Metabolites & Environmental Adaptability

In addition to metal-reducing capabilities *H. Titanicae* can synthesize bioactive molecules, including ectoine and extracellular enzymes. The strain also possesses bioremediation potential by degrading pollutants and hydrocarbons in marine environments.

The Shift Toward Aquaculture

Why Researchers Became Interested

The researchers became interested in this bacteria because it could potentially be used as a probiotic for fish and shrimp. Compared to terrestrial probiotics (e.g., *Lactobacillus*, *Bacillus*) endogenous marine bacteria are better adapted to the saline environment of aquatic animals and provide colonization advantages in the gut.

Probiotic Studies in Marine Species

The following study highlight the potential of various *Halomonas* spp. In aquaculture:

1. Turbot (*Scophthalmus maximus*): According to an article published in the Journal of Aquaculture. Bamidgeh (Xu et al. 2026) the endogenous strain of *H. Titanicae* isolated from healthy turbot gut (HT-Tc3) can improve fish growth performance, digestive enzyme activity and disease resistance.

That studies demonstrate that host-derived strains of *H. Titanicae* can be utilized as probiotics for a variety of marine species.

Key Experimental. Performance Profile

Summary of probiotics efficacy
(*Halomonas titanicae* HT-Tc3 in Turbot)

- Final Body Weight (Day 60): Increased by 34.8% (8.51 gm 0.15 g vs. 6.31 gm 0.13g in control $P < 0.05$).
- Final Body Length (Day 60): Increased by 10.2% (7.95 cm 0.56cm vs. 7.21 cm 0.54cm in control $P < 0.05$).
- Trypsin Activity (TPS): +35.0% higher in treatment group ($P < 0.05$) improving protein digestion.
- Amylase Activity (AMS): +33.3% in treatment group ($P < 0.05$) enhancing carbohydrate digestion.
- Superoxide Dismutase (SOD): +53.4% higher ($P < 0.05$) indicating improved defense.
- Alkaline Phosphatase (AKP): +82.2% higher ($P < 0.05$) suggesting enhanced immunity.
- Pathogen Resistance (*A. Salmonicida*): Survival rate was 28% in treated fish vs. 12% In control (a 16-percentage-point survival advantage) demonstrating the lasting protective effects of the probiotic.

How Does It Benefit Fish and Shrimp?

1. Gut Microbiome Modulation

The probiotic strain modulates the gut microbiota by increasing the abundance of bacterial taxa while reducing the prevalence of potential pathogens.

2. Enzyme Production & Improved Feed Utilization

By producing digestive enzymes the probiotic enhances nutrient breakdown and utilization leading to improved growth performance.

3. Competitive Exclusion of Pathogens

The mucosal adhesion properties of *H. Titanicae* HT-Tc3 allow it to colonize the intestinal epithelium displacing potential pathogens and reducing the risk of disease outbreaks.

Future Perspectives

- Precision Probiotics: Developing tailored formulations for different host species and life stages.
- Synbiotic Approaches: Exploring the use of prebiotics to enhance the colonization and efficacy of *H. Titanicae* in aquaculture.
- Microencapsulation: Encapsulating live cells to improve their survival and efficacy in commercial fish feeds.
- Sustainable Aquaculture: Advancing the use of marine probiotics as a sustainable alternative to antibiotics in aquaculture.

Conclusion

The journey of the bacterium from the wreck of the Titanic to its applications as a probiotic in aquaculture is truly remarkable. This unique microbe can be used to improve fish growth, digestion and disease resistance making it a valuable asset in aquaculture.

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Exploring Creatine in Aquafeeds: Present Status and Future Prospects

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ABSTRACT

Creatine is a multifunctional nitrogenous compound central to cellular energy buffering through the creatine-phosphocreatine system. Emerging evidence indicates its potential as a functional ingredient in aquafeeds, particularly as fishmeal is increasingly replaced by creatine-deficient plant-based ingredients. Experimental studies have reported improvements in growth, muscle accretion, body composition, feed utilization, osmo-regulatory capacity, and flesh quality; however, responses remain inconsistent across species, dietary formulations, rearing environments, and supplementation regimes. Creatine and its precursor guanidine acetic acid may also spare amino acids involved in endogenous creatine synthesis. This review critically examines current knowledge, identifies research gaps, and discusses future applications of creatine for sustainable and precision aquafeed development.

KEYWORDS

Creatine, aquafeed, growth metrics, precision formulation

Introduction

Over the past several decades, global capture fisheries have experienced a steady trajectory, largely due to the fact that majority of the commercial fisheries sector achieves its full extent or beyond its utilization limit. In contrast, the fisheries industry across the world was surged, expanding with an average annual rate of 6.7% from 1990 to 2020, establishing itself as the most rapidly growing sector in food production worldwide (FAO, 2022). Despite its ongoing expansion, aquaculture confronts significant hurdles that threaten its future sustainability, potentially compromising the functions as a economic and environmentally sustainable source of protein for a growing global population. Some underlying constrains are escalating the microbial germination through disease occurrence and stagnation in global oil and meal derived from fish. This scarcity has driven up market prices, putting additional strain on the industry (Gatlin et al., 2007; Kibenge, 2019; FAO, 2022).

In recent years, innovative strategies in developing and utilizing feed additives are crucial for enhancing the nutritional profile of aquaculture feeds, which in turn boosts feed efficiency and fish production. Among these promising additives is creatine which is a naturally occurring biochemical compound that holds potential for optimizing finfish aquafeeds. This approach could play a vital role in advancing the productivity and overall health of finfish aquaculture systems. So, through this article aim to analyze the importance of creatine in aquafeeds with its present status and future prospects.

What is creatine?

Creatine is a popular dietary supplement among athletes, known for boosting strength and endurance to elevate performance (Devries and Phillips, 2014; Waskiewicz, 2021). It is one of the important aspects of extensive research across various facets of human beings, earning recognition like a versatile and multifaceted molecule with numerous biological roles (Wallimann et al., 2011). It is a derivative of non-essential amino acids, is integral to the

creatine–phosphocreatine–creatine kinase system, which governs high-energy phosphate metabolism. This system is crucial for buffering, transporting, and regulating cellular energy. Consequently, creatine is fundamental to maintaining the energy balance and overall metabolic processes in vertebrates. Due to its pivotal role, these organisms must continually replenish their creatine reserves through dietary intake or de novo synthesis (Wyss and Kaddurah-Daouk, 2000; Turner and Gant, 2014).

Study shows that about 95% of the creatine pool is located in skeletal muscle of an organism while the remaining 5% is stored in the brain, liver and kidney (Kreider et al., 2003). In fish, the concentration of creatine per unit of body weight can be up to five times greater than in terrestrial animals, largely due to their higher proportion of skeletal muscle relative to body weight. Typically, with the help of following table we can analyse that creatine levels in fish muscle range from 2 to 7 grams per kilogram (Table 1).

Table 1: Creatine content in fish, raw meat and animal products

Sl. No.	Food source	g kg/ma ss	Reference
1.	Herring, fillet (<i>Clupea harengus</i>)	6.5–10.0	Balsom et al. (1994); Biesalski (2004)
2.	Yellowtail (<i>Seriola quinqueradiata</i>)	5	Sakaguchi et al (1982)
3.	Salmon (<i>Salmo salar</i>)	4.5	Balsom et al. (1994); Biesalski (2004)
4.	Hake (<i>Merluccius merluccius</i>)	5	Rehbein (1995)
5.	Alaska pollock (<i>Gadus chalcogrammus</i>)	4.7	Rehbein (1995)
6.	Tuna	2.7–6.5	Balsom et al. (1994);

			Biesalski (2004)
7.	Cod (<i>Gadus morhua</i>)	3–4.4	Balsom et al. (1994); Biesalski (2004)
8.	Saithe (<i>Pollachius virens</i>)	3.4	Rehbein (1995)
9.	Blue whiting (<i>Micromesistius spoutassou</i>)	3.7	Rehbein (1995)
10.	Shrimp (<i>Penaeus sp.</i>)	0.7	Rehbein (1995)
11.	Plaice (<i>Pleuronectes platessa</i>)	2	Balsom et al. (1994); Biesalski (2004)
12.	Cockle (<i>Cerastoderma edule</i>)	0.05	Rehbein (1995)
13.	Blue mussel (<i>Mytilus edulis</i>)	0.08	Rehbein (1995)
14.	Pork	5	Balsom et al. (1994); Biesalski (2004)
15.	Milk	0.1	Balsom et al. (1994); Biesalski (2004)
16.	Beef	4.5	Balsom et al. (1994);

Effect of Creatine on Product Quality, Organoleptic and Nutritional Value

Consumer demand for high-quality food has grown steadily worldwide in recent decades. In the case of meat, quality traits such as colour, flavour, and texture are central to how satisfied consumers ultimately feel with a product (Bredahl et al., 1998). Because aquaculture involves such a broad diversity of fish species, it is difficult to apply a single, universal standard for judging product quality (Kamolka et al., 2020). Nonetheless, fish flesh quality is generally understood to involve several species-specific characteristics — colour, appearance,

			Biesalski (2004)
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Purpose of creatine as supplement

The purpose of creatine supplementation is to boost both resting phosphocreatine levels and free creatine in the tissues, primarily in muscle tissue with the ultimate aim of enhancing muscular performance. Cells that have high energy demands depend on the creatine-phosphocreatine energy buffer system to regenerate adenosine triphosphate (ATP) from adenosine diphosphate (ADP), thereby ensuring a continuous supply of energy. However, once these reserves are depleted, phosphocreatine must be recycled from creatine to regenerate ATP by phosphorylating ADP (Gastin, 2001).

Creatine supplementation in aquaculture

Creatine's versatility as a supplement or feed additive has garnered significant interest across various vertebrate species. This is evident from numerous studies conducted in mammals such as livestock, laboratory animals, and companion animals as well as in birds and fish.

In teleost species, our understanding of creatine's functions is still limited compared to what is known in mammals and birds. Therefore, more research is needed to explore the diverse effects of creatine supplementation in finfish species.

odour, taste, nutritional content, and texture. Texture in particular is considered a core quality marker, shaped largely by how dry, chewy, or juicy the flesh is (Lie, 2001).

A number of studies have examined how creatine supplementation influences fish flesh quality. Schrama et al. (2018), for example, found that adding creatine to commercial diets did not meaningfully change muscle quality in gilthead seabream when evaluated through texture analysis. They did note, however, that fish receiving the higher creatine doses (5% and 8%) showed elevated pH values (around 6.5) at 24 hours after slaughter relative to fish on unsupplemented or low-creatine (2%) diets. This pattern points to creatine potentially boosting

muscle energy reserves, which in turn could benefit flesh quality — a conclusion that aligns with earlier work by McFarlane et al. (2001) on muscle glycogen levels in rainbow trout.

Similarly, Lin et al. (2023) reported that creatine-supplemented fish had higher postmortem pH at 48 hours, together with lower activity of lactate dehydrogenase and pyruvate kinase and reduced muscle lactic acid. Separately, Ramos-Pinto et al. (2019) documented a marked rise in dorsal muscle cross-sectional area in gilthead seabream fed creatine, along with a shift toward a greater share of both small- and large-diameter muscle fibres. Although this study did not directly measure texture, the structural changes observed suggest that flesh quality could plausibly improve as a result.

Tian et al. (2022) found that a 0.6% creatine inclusion improved several texture-related traits in grass carp — including hardness, gumminess, chewiness, and cohesiveness. The authors linked this to creatine's influence on myofibre diameter, fibre density, fibre-type composition, and collagen levels, which also coincided with higher levels of total protein, total and essential amino acids, and flavour-related free amino acids in the muscle, potentially improving taste as well. In contrast, the same Lin et al. (2023) study found no meaningful shifts in textural traits such as hardness, springiness, or chewiness as a result of creatine supplementation. Given these inconsistent findings, more research is clearly needed to understand how dietary creatine affects flesh quality. Future work should take into account variables such as a species' trophic level, the composition of the diet (for instance, plant-based versus fishmeal-based), and the developmental stage of the fish. It is also worth further exploring creatine's possible antioxidant role, which could help protect proteins and lipids from oxidative damage and, by extension, influence overall meat quality (Zhang et al., 2013).

Is Creatine a “Conditionally Essential Nutrient” in Fish?

A nutrient is classed as essential when an organism either cannot make it internally or cannot make enough of it to meet its physiological requirements, meaning it must come from the diet. A conditionally essential nutrient sits somewhere in between: the body can synthesise it from precursor compounds, but under certain circumstances — such as restricted dietary intake — internal production may fall short, making dietary supplementation necessary (Meyers et al., 2006). As the aquafeed sector moves toward diets containing less or no fishmeal and relies more heavily on non-fish protein sources, particularly plant-based terrestrial ingredients (Gatlin et al., 2007), several problems arise. These include imbalanced amino acid profiles — for example, inadequate methionine and lysine relative to physiological need (NRC, 2011) — as well as shortfalls in nutrients typically supplied by animal tissue, such as taurine (Hardy, 2010) and creatine (Ringel et al., 2007). Such constraints matter most for carnivorous fish species. There is currently no direct evidence describing the exact amino acid requirements for creatine synthesis in fish, but it is reasonable to assume their needs are similar to, or perhaps greater than, those documented in mammals. In mammals, creatine biosynthesis draws heavily on daily amino acid intake — consuming roughly 10% of glycine, 22% of arginine, and 42% of methionine (Kashani et al., 2020). Two further observations support the idea that fish may have comparable or higher requirements: first, creatine levels in fish muscle can reach up to 10 g/kg, exceeding typical concentrations in mammalian meats such as beef and pork (about 4.5–5 g/kg) (Balsom et al., 1994); and second, research indicates that fish may possess a greater capacity for endogenous creatine synthesis than mammals do (Borchel et al., 2019).

Conclusion

Creatine supplementation in aquafeeds presents a promising approach to enhancing the growth performance, endurance, muscle composition, and health of finfish in aquaculture. Studies have indicated that creatine can significantly improve growth rates, muscle protein content, and various biomarkers of antioxidant and immune

responses in several fish species. Future research should focus on addressing the discrepancies in results by exploring the underlying mechanisms of creatine metabolism in different fish species, optimizing supplementation levels, and evaluating its impact under various dietary and environmental conditions. Additionally, investigating creatine's role as a conditionally essential nutrient in plant-based diets could provide further insights into its broader applications in sustainable aquaculture practices.

Overall, while creatine supplementation shows a promise, a more comprehensive understanding of its effects and mechanisms will be crucial for its effective and consistent application in aquaculture.

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Artificial Intelligence for One Health in Aquaculture: A Review of Applications and Connections

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ABSTRACT

In recent years, the rapid expansion of aquaculture as a major food source highlights the interconnectedness of animal health, ecosystem sustainability, and public health, the core of the One Health approach. Simultaneously, Artificial Intelligence (AI) provides unprecedented tools to understand, monitor, and optimize these complex systems. This comprehensive review illustrates AI's transformative applications in aquaculture and assesses their direct contributions to One Health. It explores how AI-driven precision aquaculture enhances food safety through real-time monitoring of animal welfare and environmental conditions. The review covers AI's role in managing veterinary drug residues, a key One Health challenge, via predictive analytics and smart residue tracking. It analyzes AI's capacity to strengthen biosecurity through early pathogen detection and dynamic risk assessment for safer production. Furthermore, the article examines AI's adoption for sustainable aquaculture, ensuring long-term supply through resource efficiency and ecosystem monitoring. Finally, it details AI's critical function in controlling feed quality for fish health and product safety. By synthesizing current research, this article argues that strategically deploying AI is an essential enabler for operationalizing the One Health framework, ultimately safeguarding and sustaining global aquatic food systems.

KEYWORDS

Artificial Intelligence, One Health, Food Safety, Biosecurity, Sustainable Aquaculture.

Introduction

Aquaculture production around the world has surpassed capture fisheries as the largest source of fish for human consumption, due to stagnant wild stocks and increased protein demand from a growing population (FAO, 2024). This high level of production occurs under a delicate triad however: the health of cultured organisms, ecological integrity of the environment and the safety of the final product to the consumer (Boyd et al., 2022). Stress in one domain simply feeds one another, and stressors in one domain inevitably feed on to the other. Disease outbreaks cause the consumption of pharmacological drugs that may result in residues in products and affect the environmental microbiota (Wannasand Mohammed, 2025). Bad water quality stresses animals and is bad for their health and nutritional quality. Enormous feed usage contributes to nutrient loading to the environment. This interdependence is the crux of the One Health approach, a single, transdisciplinary approach that understands that the health of people, animals, plants and their common environment are inextricably linked (Danasekaran, 2024). Traditional aquaculture management usually includes manual sampling, reactive intervention, broad-spectrum treatment and so on, which is inefficient, can worsen the problems, and is not coping with dynamic systems in the long run (Yusoff et al., 2024). Artificial Intelligence (AI) including machine learning, deep learning, computer vision and Internet of Things (IoT) can handle large multivariate datasets in real time. Combining data from underwater imaging and acoustic signals, water quality sensors and genomic information, AI generates actionable, real-time insights (Rather et al., 2024; Lim, 2024; Ou, 2025). This review argues that AI is the essential enabler for making One Health to be operationalized in aquaculture. We have systematically reviewed AI across 5 key domains (Fig 1):

- 1) AI in Aquaculture Practices and Food Safety: A link between animal health, environment, and human health.
- 2) Residues of Veterinary Drugs: AI for predictive pharmacodynamics, residue monitoring, and antibiotic stewardship.
- 3) Biosecurity: AI-based for early, precise pathogen detection and dynamic risk assessment.
- 4) Sustainable Aquaculture: The application of AI for feed-precision optimization, stock monitoring and environmental impact reduction to drive long-term safe fish supply.
- 5) Feed Quality: AI for better feed formulation, for contaminant detection, and for efficient feed for animal health, and product safety.

The purpose of this article is, through a recent evaluation of present applications and future opportunities, to help present a panoramic view of intelligent systems for a more resilient, safe and sustainable aquaculture industry that is in line with One Health principles.

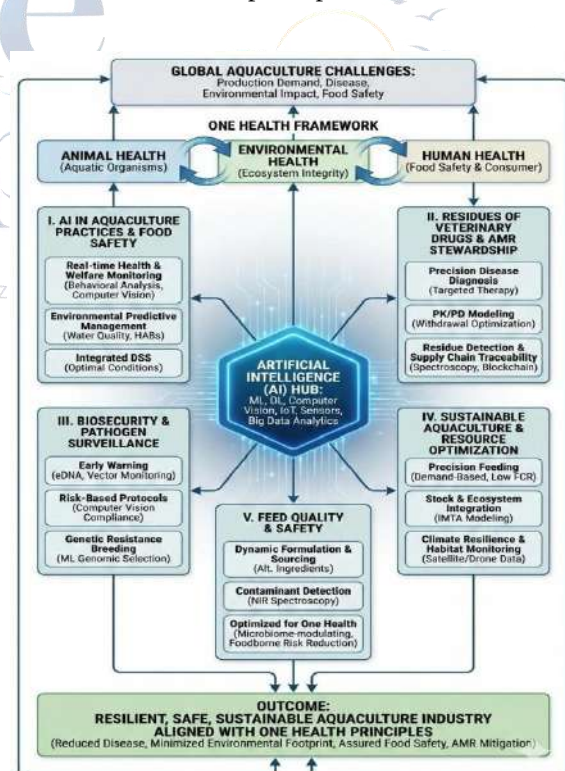


Fig 1: Artificial Intelligence in Aquaculture and One health

AI in Aquaculture Practices and Food Safety: A link between animal health, environment, and human health.

In aquaculture, food safety, health and safety in aquaculture extends long before harvest and is inextricable from the use of agricultural practices which dictate animal welfare and environmental conditions in the field of practice on-farm (Turlybek et al., 2025). AI functions as a central nervous system in farming, establishing a feedback loop between all decision making, in which the animal status, environmental conditions, management, and environment have a connection to the farm's data in a feedback loop (Michielon et al., 2024).

Health and welfare monitoring in real-time

Safe food starts with healthy animals. Computer vision with AI is changing the face of behavioral and physiological tracking (Pandey and Mishra, 2024).

Behavioral analysis: AI models that are trained on video feeds can identify and analyze fish behaviors (e.g. feeding practices, swimming behaviors, breathing mechanisms (e.g. piping) indicating water-quality problems) using deep learning (DL) approaches. The behavioral deficits of those involved in collaborative efforts are typically the first sign of stress, disease, or poor conditions. For example, decreased feeding behaviors or erratic swimming can create automated alerts to farmers for inspection (Xiao et al., 2025). This moves health management from reactive to proactive.

Individual health assessment: With modern visual systems, physical signs of disease (lesions, ulcers, parasites like sea lice) can be detected and biometric indices (length, weight) can be quantified in a noninvasive manner. Recently, high accuracy of *Aeromonas hydrophila* infection detection in carp and sea lice on salmon were found by using convolutional neural networks (CNNs) (Islam et al., 2024). This is used to allow selective culling or treatment rather than spreading the disease and unnecessary chemical usage.

Environmental monitoring and predictive management

Water quality parameters (dissolved oxygen, temperature, pH, ammonia, nitrite) are essential for fish health and impact the presence of pathogens and toxins (e.g., algal blooms). IoT sensor networks report continuous, high-frequency data (Jan et al., 2021).

Predictive analytics: ML models (e.g., regression trees, neural networks) on historical and real-time sensors provide predictions for high-hazard events, such as hazardous drops in dissolved oxygen (hypoxia) and ammonia spikes (Hridoy et al., 2025). Farmers are early aware of the impending events, which may help prevent aeration or water exchange leading to mass mortality events that may affect welfare as well as food security.

Ecosystem linkages: AI can incorporate off-farm environmental data (e.g., satellite imagery for sea surface temperature, chlorophyll-a) for risk prediction of harmful algal blooms (HABs) that may generate biotoxins, i.e., saxitoxins, accumulating in shellfish (Muhammad et al., 2026). Predictive models assist in the management of harvest closures, reducing the risks associated with paralytic shellfish poisoning (PSP) on human health (Paturi et al., 2025).

Integrated decision support systems (DSS)

AI power is in integration. DSS solutions combine data from vision, environmental sensing as well as feeding systems. Reinforcement learning methods can learn the correct controls for aeration, feeding, and stocking density which helps to ensure optimal growth and health and has a minimum environmental impact as well as resource consumption. Such comprehensive farm management contributes to safe, quality fish production as it establishes optimal living conditions across the production cycle which minimizes stress-induced disease and quality degradation (FAO and ICRISAT, 2022).

One health linkage: This continual smart monitoring provides a direct digital link between farm environment and animal health

and product safety. It reduces the requirement for medical interventions by preventing disease outbreaks and stress. Through predicting environmental threats, it protects both the cultured organism and the ecosystem, protecting native aquatic organisms and human populations that depend on those ecosystems from pollution and pathogens (Benis et al., 2023; Vlaicu et al., 2024).

Residues of Veterinary Drugs: AI for predictive pharmacodynamics, residue monitoring, and antibiotic stewardship.

The incorporation of veterinary drugs, especially antibiotics, in aquaculture constitutes a classic One Health problem. It is associated with the development of antimicrobial resistance (AMR) in water-borne bacteria, which may be transferred to humans and animals through mobile genetic elements and to the potential toxicity of residues in edible tissues exceeding Maximum Residue Limits (MRLs), where they represent a direct toxicological threat to consumers (Caneschi et al., 2023).

Precision disease diagnosis and targeted therapy

Use of indiscriminate or prophylactic antibiotics is a leading factor in residue and AMR problems. AI increases precision in diagnosis (Verma et al., 2025).

AI-powered disease detection: AI helps us spot sickness in fish quickly and accurately. Instead of guessing or using broad treatments, machine learning (ML) can look at data from simple test kits, analyze the microbes living in the water or inside the fish, or even notice unusual fish behavior. That helps pinpoint exactly what germ is causing the problem and which antibiotics might work against it. Farmers can then use the right medicine, in the right amount, which cuts down on how much and how many kinds of antibiotics are needed (Pennisi et al., 2025).

In predicting outbreaks before they take place: AI can also act as an early warning system for disease spread. Special computer models that use information about how fish

move, water currents, and previous disease history will guide how an illness might travel within a farm or jump to neighboring ones. So farmers have a chance to take smart, specific steps to stop the disease early on. By doing so, health care for the whole farm is often not needed, and fish and the environment are healthier (Rahman et al., 2024).

Pharmacokinetic/Pharmacodynamic modelling and optimization of withdrawal period

It is essential for residue compliance to find the correct dose and ensure adherence to the withdrawal period (the time from last treatment to harvest).

Personalized medicine for fish with AI: Right now, most methods for figuring out how medicines work in fish are designed for an "average" population. But AI changes the game. It can use specific details about a group of fish, like their size, the water temperature and saltiness, and how healthy they are to create customized models. These smart models then predict exactly how the drug will break down in those specific conditions and when it will be safely out of the fish's system (Pereira et al., 2022).

Smart withdrawal compliance: Blockchain combined with AI can provide immutable records for treatment. Smart feeders connected to IoT can be programmed to prevent medicated feed after a treatment cycle, and farm management software can automatically calculate and enforce a dynamic, data-based withdrawal period, detecting any stock for harvest prior to deeming it safe (Zou et al., 2020).

Residue detection and supply chain assurance

AI builds capacity for regulatory and self-monitoring.

Spectroscopic analysis: ML-based algorithms are applied to analyze complex data from hyperspectral imaging or biosensors to rapidly and non-destructively identify and quantify chemical residues in fish fillets, making

substantial progress compared with expensive and time-consuming laboratory techniques (Wang et al., 2026).

Supply chain traceability: AI algorithms can process blockchain or RFID-enabled traceability data to detect patterns suggesting non-compliance or high-risk batches before targeted inspections and recalls are implemented (Adamashvili et al., 2024).

One health linkage: AI tackles the trilemma of drug residue head-on: it's designed to ensure effective treatment for animal health, reduce environmental AMR selection pressure, and ensure residue-free food for human consumption. AI supports precision treatment and rigorous oversight, underpinning antibiotic stewardship in aquaculture, which is an important area of concern in the worldwide battle against AMR (Kasse et al., 2025).

Biosecurity: AI-based for early, precise pathogen detection and dynamic risk assessment.

Biosecurity is all actions taken to prevent introduction and/or spread of pathogens. The best sustainable defense against disease is robust biosecurity, which protects the health of animals and the safety of the food (Ahmadivand et al., 2025).

Early warning and pathogen surveillance

Environmental DNA (eDNA) and AI: The eDNA sampling for the detection of genetic traces of pathogens in water is an effective method of surveillance without the need to be invasive. For example, AI algorithms (e.g., anomaly detection models) can analyze temporal data of eDNA sequences for the detection of new or established pathogens at ultra-low concentrations, well earlier than clinical signs (Yoon et al., 2025). This enables proactive quarantine or husbandry repositioning.

Wildlife vector monitoring: Drones equipped with cameras, combined with computer vision technology, can monitor wildlife (e.g., birds, marine mammals) around farm sites, assessing their number and behavior as potential vectors of disease. This guide-posts the development of

barrier and deterrence strategies at risk (Aly and Fathi, 2024).

Risk-based inspection and biosecurity protocol optimization

Computer Vision for Compliance: Cameras at farm entrances can employ object recognition to monitor that vehicles, machinery and human operators adhere to disinfection guidelines (in this case, the use of footbaths and changing of clothes) (Rygało-Galewska and Kołnierzak, 2025).

Dynamic biosecurity risk scoring for each farm site or zone: ML models can incorporate heterogeneous risk factors (temperature changes, historical disease data, water currents, proximity to other farms, where farm stock comes from, etc.) to create dynamic biosecurity risk scores for each specific farm or zone, incorporating predictive risk models based on the risk factors and predictability. This enables prioritizing resources (for example, frequency of health checks, investment in infrastructure) according to measurable risk (MohsinRaza et al., 2025).

Genetic resistance and breeding

AI also speeds up selective breeding for disease resistance, a key biosecurity strategy. ML-based genomic selection can analyze high-density SNP (Single Nucleotide Polymorphism) chip data to correlate the genotypes and disease resistance phenotypes to accurately predict the breeding value of candidates. This leads to stocks with endogenous resilience, which lowers the population level burden of disease and then drug usage (Garcia-Oliveira et al., 2026).

One health connection: Robust AI-powered biosecurity can defend cultivated stocks, prevent pathogen contamination of wildlife populations from emerging, as well as limit human pathogen spillovers into the animal-induced wild populations, and decrease the necessity for antimicrobial treatments. It will provide the health of wild ecosystems (environmental health) and a stabilized, disease-free food production system that is disease-free

(animal health to human health) (Kasse et al., 2025).

Sustainable Aquaculture: The application of AI for feed-precision optimization, stock monitoring and environmental impact reduction to drive long-term safe fish supply.

One Health incorporates sustainability and addressing existing demands in a sustainable way that allows a healthy environment for generations to come. AI powers accuracy in precision aquaculture, optimising productivity and reducing ecological impact (Yang et al., 2025).

Precision feeding and nutrient management

Feed is also the foremost operational expense and sources of nutrient pollution (nitrogen, phosphorus) by far in our supply (Dalbem Barbosa et al., 2024).

Demand-based feeding: Computer vision systems simulate a fish appetite based on their behaviors and competition. Reinforcement learning (DL)-based controllers respond to demand in the field by altering feed to the right amount. Feed conversion ratio (FCR) and wastage decrease dramatically because of this (Thornburg, 2025). Low FCR implies less uneaten feed, which pollutes the water.

Fecal waste monitoring: Underwater cameras and images of the waste can track outflow and accumulation. This information is used to construct models that maximize waste recovery and decision about fallow (protect benthic ecosystems), for example (Ning et al., 2024).

Stock management and optimized production

AI vision system achieves accurate, frequent stock counts and size distribution analysis without the stress factor. This enhances inventory control, harvest scheduling, and grading practices, minimizing losses and providing a steady stream of goods into the market (Çaylı and Oralhan, 2024).

Integrated multi-trophic aquaculture (IMTA) modelling: IMTA co-cultures fed species (fish, etc.) with extractive species (seaweed, shellfish) that use waste nutrients.

Through the modeling of these intricate interactions between species and environmental conditions AI can lead to the establishment of strategies that maximize the nutrient recycling and economic yields through better IMTA designs in integrated systems that contribute to a more closed-loop, sustainable system (Nissar et al., 2023).

Ecosystem integration and climate resilience

AI enables farms to adapt to and address the impacts of climate change (Nikhitha and Prasanth, 2025). Climate Impact Modeling: ML can scale climate models to forecast local impacts, including on-site water temperatures, oxygen solubility, and storm frequency, to contribute to site selection, species selection and to infrastructure design that is suitable for long-term adaptation (Holt et al., 2025).

Habitat monitoring: AI analysis of satellite and drone imagery can assess the impact of farm operations on seagrass beds, mangrove forests, or coral reefs in the wild to provide adaptive management strategies for these vital ecosystems, supporting coastal protection and wild fisheries maintenance (Mohan, 2025).

One health linkage: AI-enforced sustainable practices will ensure long-term survival of aquaculture as such. Through — reducing pollution, preserving biodiversity and boosting resource efficiency, AI underpins planetary environment robustness. The reliable, safe, and nutritious food supply for global human health rests on a stable, sustainable production system (Utku and Kutlu, 2025; Bala et al., 2024).

Feed Quality: AI for better feed formulation, for contaminant detection, and for efficient feed for animal health, and product safety.

The quality of feed is the key to nutrition, health, even products. Feed sources of contaminants (mycotoxins, heavy metals, dioxins) may have a risk of accumulation in fish, resulting in human health concerns. The fish immunity and flesh quality are compromised by suboptimal formulation (Puvača et al., 2024).

AI in feed and component formulation and sourcing

Least-cost dynamic formulation: Traditional least-cost formulation uses linear programming. AI improves this by dynamically calculating real-time prices of ingredients and how varied there are with nutrients, while also measuring sustainability scores (e.g., carbon footprint, soybean sourcing). By applying chemical composition as predictive factor, ML based models can also calculate nutritional value of new alternative ingredients (e.g., insect meal, single-cell proteins) to promote its adoption (Akintan et al., 2024; Zhang et al., 2023).

Predictive nutrition: AI models link specific dietary formulations with growth metrics, for example, but also with health outcomes (e.g., gut microbiome profile, immune gene expression) and final product attributes (e.g., fillet fatty acid profile, texture). As a result, the "functional feeds" that are conducive to good healthy state and desired characteristics of a product can be developed (Agrawal et al., 2025).

Contaminant detection and supply chain integrity

Rapid feed analysis: Just like fish residues detection, applying NIR spectroscopy with ML to incoming feed batches can detect macronutrient composition and potential contaminants, like aflatoxins, at feed mill or farm reception in real time (Wang et al., 2025).

Blockchain and AI for traceability: For some high-risk ingredients such as fishmeal isolated from certain areas, for example, blockchain-based provenance information can be mined by AI for assessing the risk of contamination (e.g., history of mercury concentration) to test or source for contamination at a time before (Dhal and Kar, 2025).

Optimizing feed for health and safety results

AI can assist tailoring feeds targeting One Health objectives especially (Rather et al., 2024).

Microbiome-modulating feeds: AI can analyze a mixture of feeding components, gut microbiome data (in the form of sequencing), and disease resistance to identify prebiotic or probiotic feed strategies, which strengthen innate immunity leading to a decline in susceptibility to disease (Probul et al., 2024).

Minimizing risk of foodborne risks: A higher concentration of histamine-producing bacteria in fish species susceptible to scombroid poisoning can be minimized by making an optimized formulation, or in aquaculture with sufficient antioxidant levels that improve shelf-life and food safety would not only lead to a better outcome (Visciano et al., 2014), it also provides the best possible shelf-life as well as to be an improvement in food safety.

The one health linkage: Quality, safe, nutritious feed directly produces healthier animals (decreasing disease burden), reduces the transport of unwanted environmental contaminants to the human food chain, and thus a more food-producing product (Danasekaran et al., 2024). AI improves feed to be not only cost effective but also a vector from which health promotion through One Health can take place (Pandey et al., 2025).

Challenges, Ethical Considerations, and Future Directions

The introduction to aquaculture of AI is full of opportunities yet also challenges (Fernandes and D-Mello, 2025).

Availability and quality of data: AI can be effective only when the datasets being used are large, standardized and annotated (in aquaculture these volumes are often limited). We need collaborative data-sharing platforms (Rather et al., 2024).

Cost and accessibility: Initial investments in sensors, connectivity and expertise can be too expensive for small-scale farmers, presenting a possibility of a "digital divide" (Yang et al., 2025).

Interpretability and trust: In many cases, as many complex AI models are "black boxes," farmers and regulators might distrust these

models. We need to build explainable AI (XAI) (Saarela et al., 2024).

Cybersecurity: Secure farms are at risk of cyber threats to disturb operation, or to fabricate data with significant impacts on food safety (Maraveas et al., 2024).

Ethical and employment implications: While monitoring and decision-making are automated, the role of skilled husbandry knowledge and the threat of job displacement for workers remain in the future (Yang and Zhang, 2024).

First, we need sensors that are both affordable and tough enough for real farm life. Next, there's federated learning, a clever way to train powerful AI models without farms having to hand over their private, raw data. It's like getting the benefits of shared knowledge while keeping your own information safe. The idea of digital twins is also exciting. This means creating a live, virtual copy of the farm is a kind of simulator where different strategies can be tested (like changing feed schedules or stocking density) on the computer first, without any risk to your real fish. Finally, none of this will reach its full potential without the right policies and rules. We need smart regulations that encourage innovation but also make sure the technology is used fairly, safely, and in a way that truly protects the environment (Fernandes and DMello, 2025).

Conclusion

Artificial Intelligence in aquaculture reaches far beyond efficiency and sustainability. It has offered the tool of the trade for the interdependence and complexity of the One Health paradigm-like challenges. By allowing for real-time, in-depth oversight of animal welfare and environment, AI establishes a baseline for pre-harvest food safety. It provides a precise mechanism for dealing with the important issue of veterinary drug residues, tackling AMR. It strengthens biosecurity through intelligent monitoring and risk forecasting. It promotes production system sustainability and food security in the long term. Last but not least, it maximizes the essential feed input for the purpose of the health and

safety results. The evolution of AI is not a nice to have option when it comes to technology, but an imperative evolution for an aquaculture industry that needs to expand to support the world and to protect ecosystems and animals and people. Safe, sustainable and resilient aquatic food systems of the future are shaped by the crossfire of biological understanding and digital intelligence, all of which are anchored in the integrative philosophies of One Health.

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Tributylin as Functional Additive for Fish and Crustaceans Aquafeeds

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ABSTRACT

Tributylin, a triglyceride of butyric acid and glycerol, has emerged as a promising functional feed additive for sustainable aquaculture. Research in fish and crustaceans demonstrates that dietary tributyrin can improve growth, feed utilization, intestinal morphology, digestive enzyme activity, antioxidant capacity, immune function, and gut microbial composition. Its beneficial effects are particularly relevant in plant-based aquafeeds, where tributyrin may alleviate intestinal dysfunction associated with high levels of soybean meal and other alternative ingredients. Recent studies in largemouth bass, yellow catfish, Pacific white shrimp, and swimming crab further support its functional potential. Nevertheless, responses vary with species, diet composition, and dosage, requiring further research to optimize practical applications.

KEYWORDS

Tributylin, Intestinal health; Growth metrics; Sustainable aquaculture

Introduction

The recent surge in aquaculture production over the past few decades, along with its anticipated expansion in the future, presents a range of challenges for the industry. Recent advancements in fish nutrition research have led to creation of new, balanced commercial diets that significantly enhance fish growth and health (Makode, 2017). It has been observed that formulated feed is crucial in semi-intensive fish farming, as it is necessary to sustain higher fish densities than what natural water fertility can support. Therefore, supplementary feed is regarded as an essential strategy for boosting fish yield (Jhingran, 1991).

The stagnation of marine capture fisheries leads to more dependency on plant-based ingredients which is deficit in limiting amino acid methionine and lysine (Deborde et al., 2021), presence of anti-nutrients and deficiency in long chain polyunsaturated n-3 fatty acid [eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA)], (Alhazzaa et al., 2019; Cottrell et al., 2020). Plant-based diets can cause increase in inflammation, gut irritation, and intestinal issues, potentially contributing to the development of enteritis (Blaufuss et al., 2020; Palma et al., 2021).

Short-chain fatty acids (SCFA), includes butyric acid and its different derivative sodium butyrate, which is known to promote healing of intestine by increasing the development of epithelial cell and increases function of intestinal absorption (Abdel-Latif

et al., 2020). In formulation of feed for fish and crustaceans, SCFA is a great choice as feed additives which has promising effect in overall health as it balances gut activity, enhance immunity, along with it act as source of energy for cells of gut, anti-inflammatory properties (Tran et al., 2020).

Butyric acid and its derivatives

Butyric acid is a four-carbon odorous volatile, biologically active short chain fatty acid, which can also be produced in gut by bacterial fermentation of dietary carbohydrate including dietary fibre. It is most commonly found in two forms i.e. salt and ester form, known as butyrate and butanoate, respectively (Jiang et al., 2018).

Tributylin (TB), a triglyceride made up of butyric acid and glycerol, is a notable derivative of butyric acid that has been extensively researched and used as a feed supplement for livestock. Its application in aquafeeds, while more recent and less studied, is gaining attention. This growing interest in using dietary tributyrin for fish and crustaceans has prompted the current article, which focuses specifically on species relevant to aquaculture production.

Butyric acid: source

The advantageous effects of butyric acid on metabolism, overall health, and gut microbiota balance have led to increased interest in adding it to feeds for production animals. However, challenges such as its high volatility, strong odour, corrosiveness, and significant absorption in the upper gut can limit its

effectiveness (Bedford and Gong, 2018). Poly- β -hydroxybutyrate (PHB) is a bacterial compound used for energy and carbon storage and has been investigated as an additive in aquafeeds to enhance production in fish and shrimp. Sodium butyrate, a more stable and less odorous salt form of butyric acid, is often added to animal feeds. It can be included directly in diets or encapsulated with triglyceride coatings, depending on whether the goal is to target the small or large intestine (Abdel-Latif et al., 2020). The choice between coated and uncoated forms of butyrate, and the site of its release, should be considered based on the specific goals of supplementation during diet optimization (Ahsan et al., 2016). Conversely, Tributyrin is another butyric acid source frequently used in both human and livestock diets, and its application as a dietary supplement for fish and crustaceans has only recently started to be investigated.

Metabolism and biological function of butyric acid

Plant cell-wall polysaccharides and undigested starches from the small intestine are fermented by anaerobic microbiota in the colon, resulting in the production of short-chain fatty acids (SCFAs), primarily acetate, propionate, and butyrate (Scheppach et al., 2004). One of the most recognized effects of SCFAs is their

ability to stimulate the proliferation of epithelial cells in the intestine (Scheppach and Weiler, 2004). The mechanisms by which SCFAs promote gut health are still not fully understood and can be complex, warranting further research (Liu et al., 2018). For instance, butyrate has been shown to cross the blood-brain barrier, potentially influencing appetite and eating behaviours. Additionally, butyrate might interact with the gut-brain axis, possibly involving epigenetic mechanisms (Soret et al., 2010).

Tributyrin in aquatic animal feeds

The inclusion of humic acid, citric acid, propionic acid salts, malic acid, formic acid salts (such as potassium diformate), sodium diformate, and various mixtures of short-chain fatty acids (SCFAs) as dietary supplements has produced positive results in several fish species. Nevertheless, butyrate remains the most commonly tested short-chain fatty acid (SCFA) as a supplement in fish diets. In aquaculture species, butyrate is predominantly given as sodium butyrate (Abdel-Latif et al., 2020). Although trials of butyrate in aquatic animals are relatively new, and details of these findings are summarized in Table 2. **Table 2: Dietary supplementation of tributyrin in crustacean species**

Fish species	Dosage (%) (% purity)	Initial weight (g)	Final weight (g)	Effects	References
Pacific White-leg shrimp	0.05% 0.10% 0.15% (98%)	0.88 ± 0.02	8.21 ± 0.52	Tributyrin @ 0.10% resulted in increase	Ding et al. (2022)

(<i>Litopenaeus vannamei</i>)				d SGR, FBW and WG, intestinal digestive enzyme activities,	
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				upregulated gene expression of intestinal antioxidant and immune enzymes, increased abundance of probiotic bacteria, although reduced intestinal microbiota diversity.	
Pacific White-leg shrimp (<i>Litopenaeus vannamei</i>)	0.1%, 0.2% (60%)	0.38 ± 0.01	5.72 ± 0.24	Improved WG, SGR and PER, reduced FCR at 0.2%, increased glutathione peroxidase activity in haemolymph at 0.1% and 0.2%, without changing innate immune parameters; increase in apparent digestibility of lipid and relative mRNA expression levels of IGF-binding protein and prophenol	Lee et al. (2021)

				oxidase genes in hepatopancreas.	
Pacific White-leg shrimp (<i>Litopenaeus vannamei</i>)	1% (Not reported)	1.82 ± 0.01	5.06 ± 0.04	Tributyrin increased zootechnical performance and nutrient retention, elevated trypsin activity, triggered immune response and altered intestinal morphology.	Liu et al. (2021)

Impact of tributyrin supplementation on microbiota of gut content

Dietary tributyrin appears to reshape the gut microbial community in fish, with downstream effects on host physiology. Most of the available research on this topic has looked at tributyrin as a tool for offsetting the drawbacks of plant-heavy feeds, so data are still relatively scarce. One example comes from common carp raised on a plant-based formulation (12% fishmeal, 50% plant meal) and given four different tributyrin doses (0.05%, 0.10%, 0.20%, and 0.40%) over an eight-week trial. By the end of the period, the abundance of Proteobacteria and Actinobacteria followed a dose-dependent pattern: both groups shrank in fish receiving no tributyrin or only the lowest dose (0.05%), but expanded again at the higher doses (0.20% and 0.40%).

A separate eight-week trial in juvenile yellow drum (*Nibea albiflora*) compared a fishmeal-based diet to soybean-meal (SBM) diets supplemented with the same four tributyrin levels. Fish given the SBM diet with no tributyrin showed a drop in gut microbial diversity, which the authors interpreted as a sign of compromised gut health (Tan et al.,

2020). Looking at specific taxa, the unsupplemented SBM group was dominated by *Acinetobacter*, a genus associated with antibiotic resistance and infection risk, over the comparatively benign *Brevundimonas*. That balance reversed in the fishmeal group and in the SBM group receiving 0.10% tributyrin, where *Brevundimonas* became the dominant genus instead. The proposed mechanism is that butyrate released during tributyrin breakdown shifts the local pH, favoring bacteria capable of breaking down and denitrifying organic material — a change that may in turn improve how well the fish digest soy protein (Tan et al., 2020).

Conclusion

Tributylin supplementation in feeds for production animals demonstrates significant potential for enhancing overall animal performance, welfare, and productivity, offering a promising alternative to reduce antimicrobial use in livestock. For aquatic animals, especially fish, tributyrin has been primarily tested in scenarios with high fishmeal replacement and has shown benefits in mitigating some negative impacts, such as gut inflammation, associated with high plant ingredient inclusion. Evaluating different levels of tributyrin across various feed formulations and species could lead to improved aquaculture feeds, optimizing tributyrin's potential to enhance production conditions and animal health. Further research into how tributyrin is metabolized and interacts with gut microbiota will clarify its mechanisms and benefits for fish performance and welfare.

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The Future on Ice: Emerging Technologies in Fish Processing

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ABSTRACT

The global fish processing industry is undergoing a significant transformation driven by the need for improved product quality, extended shelf life, enhanced safety, and greater sustainability. This paper reviews emerging technologies reshaping the sector, including advanced freezing methods such as ultrasound-assisted and high-pressure freezing, which minimize ice crystal damage and preserve textural and nutritional integrity. Non-thermal processing techniques, including high-pressure processing, pulsed electric fields, and cold plasma, are examined for their ability to inactivate pathogens and extend shelf life while retaining sensory qualities. The integration of automation, robotics, and machine vision in filleting, sorting, and quality inspection is discussed as a means of increasing processing efficiency and reducing labor dependency. Additionally, the paper explores the role of smart packaging, biosensors, and blockchain-based traceability systems in ensuring food safety and supply chain transparency. Environmental considerations, such as waste valorization and energy-efficient cold chain management, are also addressed as critical components of sustainable fish processing. By synthesizing recent advances across these domains, this paper highlights the trajectory of innovation poised to redefine fish processing practices, offering insights for researchers, industry stakeholders, and policymakers seeking to balance technological progress with sustainability and food security goals.

KEYWORDS

Smart packaging; food safety; cold chain management; automation and robotics

Introduction

Seafood processing is among the oldest sectors of the food industry, but it is currently experiencing rapid technological transformation. Global aquatic animal production is continuing to expand, with the Food and Agriculture Organization of the United Nations forecasting further increases in production, consumption, and international trade over the coming decade (FAO, 2026). Meanwhile, seafood processors are facing challenges such as increasing labour expenses, more stringent food-safety and traceability requirements, and growing consumer demand for detailed information about the origin and handling of seafood products. These factors are accelerating the adoption of automation, artificial intelligence, digital traceability systems, and energy-efficient cold-chain technologies across the industry.

This review examines the key technological developments that are transforming modern fish and seafood processing. Major areas include robotic and automated processing systems, artificial intelligence-based quality assessment and grading, block chain-enabled traceability, smart cold-chain and packaging sensors, recirculating aquaculture systems (RAS) that support a reliable supply of seafood for processing, and sustainability-focused innovations in packaging and by-product utilization. The review integrates recent industry reports, FAO information, and peer-reviewed research on emerging sensor, processing, and packaging technologies.

Automation and Robotic Processing Lines

Automating fish filleting, skinning, deboning, and sorting has traditionally been difficult because fish differ considerably in size, shape, weight, and body structure compared with more uniform animal products. Recent technological developments, however, are making these operations increasingly suitable for automation. Modern processing facilities are incorporating machine-vision technologies with robotic systems

that can identify the individual shape and dimensions of fish and adjust cutting operations accordingly. These systems can improve processing speed, increase product recovery, and reduce material losses while also decreasing the physical strain associated with repetitive manual processing activities (Sasidharan et al, 2026).

The adoption of automated equipment is also being supported by the need for improved food safety, process consistency, and operational efficiency. Advanced processing machinery increasingly incorporates sensors and automated control systems that can support compliance with food-safety measures like Hazard Analysis and Critical Control Points (HACCP), as well as the quality standards and regulations proposed by the USDA in other countries. In addition, automated systems provide more energy efficiency and improved monitoring of processing operations (Insights, F. B. 2022). Automation has consequently become an important component of large-scale seafood processing. Industrial facilities are increasingly using technologies such as automated filleting and portioning equipment, machine-based grading systems, spiral freezers, and computerized refrigeration-monitoring systems. The continued expansion of these technologies reflects the industry's demand for higher productivity, consistent product quality, reduced labor dependence, and improved resource efficiency. Market projections indicate that the seafood-processing equipment sector, including robotic filleting, portioning, sorting, and grading technologies, is expected to maintain steady growth during the coming decade (Sasidharan et al, 2026).

AI-Driven Quality Control and Freshness Sensing

Machine vision and artificial intelligence are becoming increasingly potent components to measure the quality and safety of seafood. Camera-based systems combined with machine-learning and deep-learning algorithms can assess characteristics such as fish size, shape, colour,

visible defects, and freshness rapidly and without damaging the product. Compared with conventional manual inspection, these technologies can provide more objective, consistent, and repeatable quality assessments and are increasingly being investigated for applications in automated seafood processing and grading (Zheng et al., 2026; Tariq et al., 2025).

Alongside computer-vision technologies, considerable research is being directed toward intelligent packaging systems that can monitor seafood quality during storage and distribution. These systems incorporate sensors and indicators capable of detecting changes in temperature, pH, gases, and other spoilage-related parameters. Radio-frequency identification (RFID), time-temperature indicators, pH-sensitive films, and gas sensors are among the technologies being explored for real-time monitoring of seafood freshness and storage conditions (Abedi-Firoozjah et al., 2023; Nami et al., 2024).

Colorimetric indicators are particularly promising because they can provide a simple visual indication of deterioration through changes in colour. Natural pigments and pH-sensitive materials can respond to volatile compounds and chemical changes associated with microbial spoilage. In seafood packaging, sensors designed to detect compounds such as ammonia (NH_3), hydrogen sulfide (H_2S), and total volatile basic nitrogen (TVB-N) have received considerable attention because these substances are important indicators of protein degradation and loss of freshness (Nami et al., 2024; Panwar et al., 2024). Recent developments in intelligent packaging are also combining sensor technologies with digital image analysis and mathematical or machine-learning models, creating opportunities for more quantitative and real-time assessment of seafood quality (Ameri et al., 2024).

Digital Traceability: Blockchain and Supply Chain Tracking

“Ocean-to-plate” traceability is increasingly becoming an important requirement

in international seafood supply chains, particularly as regulators, retailers, and consumers demand greater transparency regarding the origin, handling, and sustainability of seafood products. Digital technologies such as blockchain, Internet of Things (IoT) devices, and electronic tracking systems can connect information across different stages of the supply chain, allowing details such as catch location, fishing vessel, processing records, and cold-chain conditions to be recorded and accessed more efficiently. These technologies can improve transparency, support seafood safety and authenticity, strengthen efforts to address illegal, unreported, and unregulated (IUU) fishing, and increase consumer confidence in sustainably sourced products (Zhang et al., 2021; Shamsuzzoha et al., 2024). Recent research also highlights that digital traceability can improve market access and supply-chain efficiency, although high implementation costs, limited digital infrastructure, interoperability problems, and unequal access to technology remain important challenges, particularly for small-scale producers (FAO, 2007; Xue-Lønmo et al., 2026).

Smart Cold Chains and IoT Monitoring

Refrigeration, chilling, and freezing are among the most energy-demanding operations in seafood processing, making efficient cold-chain management essential for maintaining product quality, safety, and shelf life. Increasingly, Internet of Things (IoT)-based sensors, RFID devices, wireless communication systems, and real-time data platforms are being used to continuously monitor temperature, humidity, location, and other environmental conditions throughout storage and transportation, replacing conventional manual and periodic monitoring. These technologies can provide early warnings of temperature deviations, support freshness and shelf-life assessment, improve traceability, and reduce spoilage and distribution losses. Recent developments are also integrating IoT monitoring with artificial intelligence, blockchain, and other digital technologies to enable more predictive and

transparent cold-chain management across seafood supply networks (Harriz et al., 2025; Subash et al., 2024).

Recirculating Aquaculture Systems (RAS) Upstream of Processing

Recirculating aquaculture systems (RAS) are increasingly being adopted as controlled, land-based production systems capable of supplying a consistent volume of fish to seafood processing industries while using substantially less water than conventional aquaculture. Recent technological developments have focused on improving system efficiency through optimized filtration, system integration, energy management, real-time water-quality sensors, and artificial-intelligence-based monitoring. These advances are particularly relevant to the production of high-value species such as Atlantic salmon, for which land-based RAS can provide greater environmental control and biosecurity, although energy consumption remains an important challenge to their sustainability. The integration of sensors and AI-based data analysis can support continuous monitoring of parameters such as temperature, dissolved oxygen, pH, and ammonia, enabling earlier detection of abnormal conditions and more efficient system management (Badiola et al., 2018; Brown et al., 2025).

Sustainable Packaging and Byproduct Valorization

Sustainability considerations are increasingly influencing packaging, energy use, and waste-management practices within the seafood-processing industry. Processing facilities are adopting recyclable and bio-based packaging materials, water-reuse systems, energy-efficient refrigeration, and improved freezing technologies to reduce resource consumption and minimize environmental impacts. In particular, efficient refrigeration and freezing systems can help reduce energy demand while maintaining stable storage temperatures, thereby limiting quality deterioration and food losses. Research on seafood-processing sustainability also emphasizes

the importance of improving resource efficiency and recovering value from processing residues rather than treating fish by-products as waste (Hall et al., 2013).

At the same time, advances in intelligent packaging are creating new opportunities for reducing seafood waste throughout the supply chain. Smart packaging can incorporate freshness indicators, time-temperature indicators, gas-sensitive materials, and digital sensing technologies that provide information about changes in product quality during storage and transportation. These systems can help processors, distributors, retailers, and consumers make better decisions about product handling and inventory management, potentially reducing unnecessary disposal of seafood while maintaining food safety and quality (Ghaani et al., 2016; Yildirim et al., 2018).

Challenges and Adoption Barriers

The adoption of automation, artificial intelligence, robotics, and sensor-based technologies in seafood processing remains uneven because implementation requires substantial capital investment, technical infrastructure, and trained personnel. These challenges are particularly important for small and medium-sized processors, which may have limited financial resources and difficulty integrating advanced equipment into existing processing systems. In addition, the biological variability of fish, differences in species and body morphology, and the need for frequent system calibration can reduce the flexibility and reliability of automated technologies. Consequently, the transition toward digital seafood processing requires not only investment in equipment but also workforce training, technical support, and appropriate digital infrastructure (Yadav et al., 2026; Subash et al., 2024).

Smart packaging and AI-based freshness-monitoring systems also face limitations when moving from laboratory research to commercial

applications. Variations in temperature, humidity, lighting conditions, packaging materials, fish species, and product characteristics can influence sensor performance and the accuracy of AI-based models. Recent research emphasizes the need for further validation under actual transportation, storage, and retail conditions before these technologies can be widely implemented. The cost of sensors and digital monitoring systems may also restrict their use in lower-value seafood products, making adoption more economically attractive for premium, highly perishable, or export-oriented products (Ramlah et al., 2026; Nami et al., 2024).

Broader economic and supply-chain uncertainties can further influence investment decisions within the seafood sector. Changes in international trade, transportation costs, energy prices, and market conditions can affect the economic feasibility of adopting advanced processing and digital technologies. In response, seafood businesses are increasingly emphasizing operational efficiency, supply-chain resilience, automation, and better integration of production, processing, storage, and distribution activities. However, ensuring that technological progress benefits smaller processors and producers remains an important consideration for achieving an inclusive and sustainable digital transformation of the seafood industry (Subash et al., 2024; Yadav et al., 2026).

Conclusion

The technologies discussed—including automation, computer vision, blockchain, and connected sensor systems—are not exclusive to the seafood industry, as they are already being applied across various food-processing sectors. However, their rapid integration within seafood processing represents an important technological shift for an industry that has traditionally adopted advanced technologies more slowly than many other food sectors. The increasing combination of automated processing, digital traceability, intelligent monitoring, and energy-efficient cold-

chain systems is expected to improve productivity, product quality, food safety, resource efficiency, and supply-chain transparency. Seafood processors that adopt flexible and scalable technologies are therefore likely to be better prepared to respond to growing global seafood demand, stricter regulatory requirements, sustainability expectations, and increasing consumer interest in knowing the origin and production history of seafood products.

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Cold Plasma: An Electric Wind That Can Transform the Way We Preserve Fish

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ABSTRACT

Fishes and other aquatic foods are highly susceptible to spoilage because of their high levels of water content, proteins, and unsaturated fats, and thus efficient preservation is very essential to the seafood industry. Traditional techniques such as cooling, freezing, canning, and smoking have proven to be quite effective in preserving seafood but they often affect the taste or the nutritive quality of the food. Cold plasma (CP), a non-thermal technique that involves the ionisation of gases at ambient temperature, is being considered as a viable means of preserving fish without damaging it or leaving any chemical traces. The following discussion will examine some of the latest studies carried out in relation to CP and plasma-activated water and ice in fish preservation and their applications.

KEYWORDS

Cold plasma; Fish preservation; Non-thermal processing; Plasma-activated water; shelf life

Introduction

As you stroll past the aisles of a fish market, the worst enemy in the room isn't another consumer trying to haggle for a better deal – it is time. The moment the fish is taken out of the water, enzymes, bacteria, and oxygen work together in their efforts to destroy what the nature has spent years producing. For many decades, the food industry has tried to win against these forces using such methods as ice, salt, smoke, and heat. Now, a new invention, used in physics laboratories, has provided a completely new option.

Cold Plasma

Plasma has been referred to as an electrically excited glowing gas – the very same principle which illuminates neon lights and gives the northern lights their brilliance. Cold or "non-thermal" plasma is produced by subjecting a gas such as air, nitrogen, or oxygen to an electric field at around or just below room temperature. It produces a combination of reactive molecules and particles such as electrons, ions, and reactive oxygen and nitrogen species without the high temperatures associated with flames and sparks. Since it maintains a low temperature, it can be used directly on food and will not cook it.

Cold plasma has been referred to as an entirely new, non-thermal process for agriculture and food industries since the specific mechanism of action of plasma is yet to be fully understood while already demonstrating its benefits in the laboratory setting (Cherif et al., 2023). In contrast to freezing or pasteurization, it utilizes no high temperatures, and unlike chemical dips, there is no residue since the reactive species formed disappear very quickly (Jiang et al., 2022).

Why Fish Requires a New Preservation Method

The nature of fish and shellfish makes it particularly prone to decay. The presence of water and unstable fats, as well as delicate protein, makes it highly attractive to spoilage bacteria and oxidation, which lead not only to

decreased shelf life but also to food safety issues that arise before the food even becomes visually and odorous unacceptable (Rathod et al., 2021). There are already proven techniques of fish preservation such as chilling, freezing, canning and smoking but each has its drawbacks as freezing degrades the texture, smoking changes the taste while heat treatment damages vital nutrients contained in fish.

Application of cold plasma technique may allow overcoming this problem by attacking the spoilage microorganisms directly at the site of the potential contamination without causing any harm to underlying tissues due to temperature.

What the research tells us

Early trials have been promising. Untreated fish showed a significant shelf-life extension when packaged with herring which had undergone in-package atmospheric plasma treatment because of decreased microbial growth inside the sealed package itself (Albertos et al., 2019). Antimicrobial effects have also been reported against foodborne pathogens such as *Listeria* and *Staphylococcus aureus* in ready-to-eat fish products, indicating that the technology could improve food safety as well as freshness (Hajhoseini et al., 2020).

But the technology isn't just about treating the fish. Researchers have also experimented with "plasma-activated water" — normal water bristling with the same reactive species created by a plasma discharge — as a rinse or ice-making medium. Research has shown that the composition of the fish itself, such as the levels of fat and protein, can influence the effectiveness of this activated water in killing microbes, indicating that treatment procedures may need to be adapted on a species-by-species basis (Zhao et al., 2020).

More recently, plasma-activated ice has moved out of the lab. An industrial-scale trial on sea bream filets found that fish packed in plasma-activated ice saw its shelf-life extended by approximately 74%, compared to around 42% for filets simply rinsed in plasma-activated water, alongside a favorable cost analysis for

processors considering the switch (Giannoglou et al., 2026).

In fact, cold plasma has shown potential against viruses: one study showed that an atmospheric pressure plasma jet could inactivate norovirus, a frequent cause of foodborne illness, on salmon sashimi—a product that, because it is eaten raw, cannot be protected at all by standard heat treatment (Huang et al., 2021).

Not a Silver Bullet — For Now

The promise is there, but researchers are honest about what the technology can and can't do. Some reviewers say cold plasma can enhance lipid oxidation in fatty fish, which can affect flavor and nutritional quality if treatment parameters are not controlled properly (Rathod et al., 2021). The results are also very diverse depending on the plasma generator, the gas mixture, the duration of the treatment and even the fish species treated, so it is still difficult to establish a single industry standard (Kulawik and Tiwari, 2019).

The other major issue is the expense and size. Most studies conducted so far have been performed using small, laboratory sizes of plasma units, and applying them to full commercial fish-processing lines — where enormous amounts of fish are handled every day in the process — is yet to be accomplished, although the latest industrial tests are showing that things are changing.

Importance Beyond Fillet

Cold plasma is important not just on fish counters. Since the technology is based on electricity and air or gas, without requiring any chemicals or huge amounts of hot water, it complies with the requirements of the food industry for green and sustainable processing. Furthermore, it can be used in other aspects, such as the sanitisation of packaging, equipment, or even wastewater from seafood facilities (Jiang et al., 2022).

Applications in Fish Processing

The function of cold plasma in the sector of fish industry has now spread widely through different aspects of the value chain such as:

- Surface decontamination of whole fish, fillets, and shellfish (e.g., sea bass, sea bream, tilapia, shrimp) preventing spoilage bacteria and extending the life of chilled fish (Rathod et al., 2021).
- Plasma activated water and plasma activated ice used as antimicrobial rinse or chilling medium during transport and storage resulting in considerable shelf-life extension over 70% in the experiment (Giannoglou et al., 2026).
- Treatment inside the package of ready-to-eat vacuum fish products producing plasma inside the sealed package to keep the food uncontaminated after the process (Albertos et al., 2019).
- Pathogen and virus removal from raw and minimally processed products, for instance, sashimi, where there is no possibility to apply heat treatment (Huang et al., 2021).
- Sanitization of processing equipment, packaging materials, and plant wastewater thereby meeting the requirements of wider hygiene and sustainability goals pursued by the facility (Jiang et al., 2022).

Benefits of Cold Plasma Technology

- Maintains nutrient and sensory quality: since the treatment is applied near room temperature, sensitive nutrients like Omega 3 fatty acids, protein, and the original texture are retained compared to thermal treatment (Cherif et al., 2023).
- Environmentally safe: generated reactive species are decomposed after treatment and there is no artificial additive or chemical residue on fish (Jiang et al., 2022).
- Wide-spectrum efficiency: cold plasma has been found to destroy food spoilage organisms, pathogens like *Listeria* and *Staphylococcus aureus*, and viruses like norovirus (Hajhoseini et al., 2021).
- Eco-friendly production method: the procedure is based on electricity only, which does not involve a huge amount of heated water

or chemical disinfectants used in traditional preservation processes (Jiang et al., 2022).

- **Application versatility:** Apart from just seafood, the same system cleans packaging, processing machines, and wastewater from the facility, and it can be supplied in the form of plasma-activated water or ice giving the technology more adaptability for different parts of the food supply chain (Giannoglou et al., 2026).
- **Applicable to packaged and raw products:** Since the process does not require heat, cold plasma can be generated within sealed packages, or used on raw ready-to-eat products like sashimi, which can't be otherwise treated with heat (Albertos et al., 2019; Huang et al., 2021).

Drawbacks and Challenges

- **The risk of lipid oxidation:** in oily fish species, the reactive oxygen species released during treatment may increase lipid oxidation which can adversely change the taste, color and nutritional value of fish (Rathod et al. 2021).
- **Variability and lack of standardization of results:** the outcome of treatments is affected by the type of plasma-generating equipment, gas composition, level of voltage, duration of exposure, and the type of fish, and that complicates the establishment of standard protocols in the industry (Kulawik and Tiwari, 2019).
- **Limited large-scale validation:** majority of studies conducted so far have been performed with the help of small laboratory-scale plasma setups, while the results of commercial application of continuous methods are still insufficient (Giannoglou et al., 2026).
- **Cost of equipment and operation:** High voltage plasma generation equipment and specialized gas are considerable investments in starting up operations, acting as a deterrent to small operatives.
- **Unclear regulations:** Transparent and coordinated food safety regulations and approval mechanisms of cold plasma technique involving seafood are still being formulated.

- **Need for species-specific optimization:** Fish composition (fat, protein, moisture) affects treatment efficiency, and hence methods can't be used directly across the fish types (Zhao et al., 2020).

Future scope

In order for cold plasma to convert from an area of interest in research to a commonplace industrial technology, various changes need to take place. Standardization of treatment protocols that include the type of gas, voltage and exposure time might be the key to normalizing contradictory results that different fish species and treatment technologies demonstrate (Kulawik and Tiwari, 2019). Continuous decrease in costs and the emergence of bigger and endless plasma systems is of paramount importance for implementation of the technology on high-capacity production lines and is based on the achievements that were reached during pilot investigations (Giannoglou et al, 2026). Combining cold plasma with other hurdle technologies such modified atmosphere packaging, natural antimicrobials or edible films is likely to compensate for the drawback of this method that promotes oxidation of fats. Additionally, clear regulations and safety standards in countries that dominate in terms of fish production and import will be set before this technology becomes widely used. Finally, in the distant future, inclusion of real-time quality monitoring devices and life cycle assessments might assist producers in developing optimal treatment protocols for every species as well as in calculating the impact of chemical preservatives replacement by physical techniques.

Conclusion

All things considered, the available data indicates that cold plasma technology is among the most viable forms of non-thermal technology to arise recently within the seafood industry. It targets two major threats to fish quality, namely, microbial spoilage and enzymatic degradation, without the risk of heat-based damage, presence of chemical residues, or

loss of flavor experienced with traditional methods of preservation. The transition of cold plasma from laboratory tests to pilots being conducted at the industrial scale with products such as sea bream fillets proves that this technology is applied in practical conditions of production, distribution, and sale of the product (Giannoglou et al., 2022).

However, it is safe to say that cold plasma technology serves as a promising new technique rather than as an alternative to established methods such as cooling, freezing, or simply following hygiene rules. It remains true, however, that the performance of the technology is very much dependent on the design of the equipment, composition of the gas, treatment duration, and the kind of fish being processed (Rathod et al., 2021; Kulawik and Tiwari, 2019). The success of the venture relies on three particular factors: further standardisation of the treatment procedure across the board, a decrease in prices of the technology as more and more seafood processors implement cold plasma processing on a larger scale, and a comprehensive regulatory framework in the world's largest seafood exporting countries. If these factors are met, cold plasma should be able to transition from a scientific experiment to a commonplace step in the fish processing process.

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From Fish Processing Waste to Value-Added Products: Innovation for a Sustainable and Circular Blue Economy

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ABSTRACT

Fish processing generates enormous quantities of by-products—heads, skins, bones, viscera, scales, and shells—that are frequently discarded despite holding substantial biological and economic value. As global seafood consumption rises, so does the volume of this waste, creating both an environmental burden and a missed opportunity for resource recovery. Emerging technologies now allow these residues to be transformed into valuable products such as fish protein hydrolysates, collagen and gelatin, chitosan, fish oil rich in omega-3 fatty acids, bioactive peptides, fertilizers, and biofuels. Such valorization not only reduces pollution and disposal costs but also opens new revenue streams for fishery-based industries, aligning with the principles of a circular economy. This article explores the diverse pathways for converting fish processing waste into commercially viable and nutritionally beneficial products, highlighting recent innovations in extraction and processing techniques.

KEYWORDS

Fish waste valorization; Circular economy; Blue economy; By-product utilization; Bioactive compounds

Introduction

Fish processing generates a considerable quantity of residual biomass that does not reach consumers as edible fillets. Depending on the species and processing method, approximately 50–70% of the original fish biomass may remain as by-products, including heads, skin, bones, scales, viscera, fins, and trimming residues (Kaushik et al., 2025; Jimenez-Champi et al., 2024). Traditionally, these materials have been discarded, landfilled, or converted into relatively low-value products such as fishmeal and animal feed. Globally, fish-processing by-products are estimated to account for approximately 50–130 million tonnes annually, indicating the enormous quantity of potentially valuable biomass that remains underutilised (Haque et al., 2026).

Rather than being regarded solely as waste, these materials are increasingly recognised as valuable secondary raw materials. Fish-processing residues contain proteins, collagen, gelatin, lipids, omega-3 fatty acids, minerals, enzymes, peptides, and other bioactive compounds that can be recovered and utilised in food, nutraceutical, pharmaceutical, cosmetic, feed, and biotechnology applications (Rigueto et al., 2023; Jimenez-Champi et al., 2024).

This concept is closely associated with the blue economy and circular economy, which emphasise efficient utilisation of aquatic resources while minimising environmental impacts. Fish by-product valorisation involves converting processing residues into useful and commercially valuable products rather than treating them as waste. Such approaches can reduce disposal problems, improve resource efficiency, generate additional revenue, and contribute to a more sustainable seafood sector (Rigueto et al., 2023; Haque et al., 2026).

A Problem Hiding a Resource

Fish-processing by-products retain considerable nutritional and functional value. Heads, frames, bones, and trimmings contain proteins, minerals, and lipids, whereas skin and scales are important sources of collagen and

other structural proteins. Fish viscera also contain proteins, lipids, enzymes, and other compounds with potential applications in food, nutraceutical, pharmaceutical, and industrial sectors (Blanco et al., 2017; Wang et al., 2024). However, these residues are highly perishable due to their high moisture content and the activity of endogenous enzymes and microorganisms. Improper handling and disposal can result in environmental pollution and the loss of potentially valuable biological resources. Consequently, increasing attention is being given to valorisation technologies, including enzymatic hydrolysis, fermentation, extraction, and other green-processing approaches for recovering high-value compounds from seafood residues (Waqar et al., 2025; Rigueto et al., 2023).

Turning Fish Trimmings into Nutrition: Protein Hydrolysates

One of the important approaches for recovering value from fish-processing residues is enzymatic hydrolysis. In this process, proteolytic enzymes break down proteins present in fish heads, frames, skin, bones, viscera, and other tissues into smaller peptides and soluble protein fractions. The resulting fish protein hydrolysates (FPHs) have demonstrated several biological activities, including antioxidant, antihypertensive, and antimicrobial properties. These characteristics make them promising ingredients for functional foods, nutraceuticals, and aquaculture feeds (Nemati et al., 2024; Cassol et al., 2025; Fan et al., 2026).

Enzymatic hydrolysis is also attractive from an environmental perspective because it can be carried out under relatively mild conditions compared with some conventional chemical treatments. Consequently, it provides a promising route for converting low-value fish-processing residues into higher-value protein ingredients while supporting resource recovery and circular-economy principles (Baraiya et al., 2025; Nemati et al., 2024).

Skin and Scales: Collagen and Gelatin

Fish skin, scales, bones, and related processing residues are important sources of collagen and gelatin. Marine-derived collagen has gained attention as an alternative to mammalian collagen because it can reduce concerns related to zoonotic disease transmission and religious or cultural restrictions. In addition, fish-processing residues provide relatively inexpensive raw materials for collagen recovery. Recovered fish collagen has potential applications in food products, nutraceuticals, cosmetics, pharmaceuticals, tissue engineering, and biodegradable materials. These diverse applications have increased interest in fish-derived collagen as a commercially valuable biomaterial rather than simply a processing residue (Rajabimashhadi et al., 2023; Rigueto et al., 2023).

Shellfish Processing Waste: Chitin and Chitosan

In addition to fish-processing residues, crustacean processing waste represents an important source of valuable biomaterials. Shrimp, crab, lobster, and other crustacean shells contain substantial quantities of chitin, which can be converted into chitosan. Chitosan is a biodegradable and biocompatible polymer with applications in biomedical materials, pharmaceuticals, cosmetics, food systems, water treatment, and biodegradable packaging. Conventional extraction generally involves acidic and alkaline treatments. However, enzymatic and fermentation-based approaches are increasingly being explored to reduce the dependence on harsh chemicals and minimise the environmental impact of chitin and chitosan production (Zou et al., 2021; Younes & Rinaudo, 2021).

Fish Oils Rich in Omega-3 Fatty Acids

Fish-processing residues such as viscera, heads, frames, and trimmings can also provide valuable marine oils containing long-chain omega-3 fatty acids, particularly eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA). These fatty acids

are nutritionally important and are widely incorporated into functional foods and dietary supplements. Several separation and purification technologies, including urea complexation, molecular or short-path distillation, and enzymatic fractionation, can be used to enrich or purify EPA and DHA from fish oils. These approaches increase the value of oils recovered from processing residues and provide alternatives to their use solely in low-value applications (Gámez-Meza et al., 2003; Aursand et al., 2014).

Fish By-products for Biodegradable Packaging

Another emerging application of seafood-processing residues is the production of biodegradable packaging materials. Fish proteins, collagen, gelatin, chitin, and chitosan can be processed into films and coatings with potential applications in food packaging. The development of these materials provides an opportunity to replace or reduce dependence on petroleum-derived plastics while simultaneously creating value from seafood-processing residues. However, many of these technologies are still at laboratory or pilot scale, and further improvements are required in mechanical strength, barrier properties, stability, processing performance, and economic feasibility before large-scale commercialisation (Lionetto & Esposito Corcione, 2021).

Beyond Fish: Toward an Integrated Marine Bioeconomy

Seafood by-product valorisation can extend beyond the recovery of individual products. Crustacean shells, for example, contain chitin, proteins, minerals, and carotenoid compounds such as astaxanthin. Similarly, fish tissues and organs can provide proteins, peptides, lipids, enzymes, and other bioactive compounds. Following the extraction of high-value components, the remaining biomass can be used for fertilisers, biofuels, anaerobic digestion, or other energy-recovery processes. This integrated approach is consistent with the

concept of a marine biorefinery, in which multiple valuable products are recovered from a single processing stream rather than relying on a single end product (Caruso et al., 2020; Maschmeyer et al., 2020).

Linking the Circular Economy with the Blue Economy

Fish by-product valorisation provides a practical connection between the circular economy and blue economy. Instead of treating harvesting, processing, consumption, and disposal as independent stages, a circular approach connects these stages so that materials generated at one stage become useful inputs for another. For example, a fish-processing facility could potentially recover protein hydrolysates from protein-rich residues, collagen from skin and scales, oils from fatty tissues, minerals from bones, and enzymes or other bioactive compounds from viscera. Such integrated utilisation can improve resource efficiency, reduce disposal requirements, and create additional economic opportunities within the seafood sector (Rigueto et al., 2023; Maschmeyer et al., 2020).

Challenges in Commercialisation

Despite its considerable potential, large-scale valorisation of seafood by-products continues to face several challenges. The composition and quality of processing residues can vary according to species, season, geographical origin, processing method, and storage conditions. Furthermore, extraction and purification technologies may involve significant capital and operating costs.

Maintaining the quality and stability of recovered compounds is another important consideration. Regulatory requirements can also influence the commercialisation of products intended for human consumption, nutraceutical applications, pharmaceuticals, and other high-value markets (Kaushik et al., 2024).

Future Prospects

A major priority for the seafood industry is to translate promising laboratory-scale extraction and valorisation technologies into economically competitive industrial processes. Future research should therefore focus on improving process efficiency, reducing energy and chemical requirements, developing integrated biorefinery systems, and establishing economically viable methods for the recovery of multiple products from the same processing stream. With continued technological development, seafood-processing residues can serve as raw materials for collagen, gelatin, protein hydrolysates, omega-3 oils, chitin, chitosan, bioactive compounds, biodegradable packaging, fertilisers, and energy products. Their systematic utilisation can reduce environmental pressure while creating additional economic value for seafood processors and coastal communities.

Conclusion

Fish-processing by-products should increasingly be regarded as valuable resources rather than unavoidable waste. Their conversion into high-value products such as protein hydrolysates, collagen, gelatin, omega-3 oils, chitin, chitosan, bioactive compounds, and biodegradable packaging demonstrates the potential of seafood valorisation to support both environmental sustainability and economic development. By integrating multiple recovery technologies within a circular production system, the seafood sector can reduce waste, improve resource efficiency, create additional revenue streams, and contribute to a more sustainable blue bioeconomy. Thus, fish by-product valorisation represents an important pathway for transforming an environmental challenge into an opportunity for innovation, resource conservation, and sustainable growth (Caruso et al., 2020; Rigueto et al., 2023).

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Integrated Multi Trophic Aquaculture: An Ecofriendly Approach towards Sustainable Aquaculture

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ABSTRACT

For the millions of people worldwide the ecosystem approach for aquaculture promotes the rational use of the nutrients as well as sustainable growth of environment. The development of modern techniques of aquaculture like Integrated multi trophic aquaculture (IMTA) played a key role in this process. This technology not only minimizes the risk of crop failure but also utilizes the waste generated during the process for nutrition purpose, which leads to the cutting down of cost and sustainable environment growth is also observed. It has given a new hope towards the sustainable aquaculture goal to be achieved.

KEYWORDS

IMTA, Filter feeders, Eco-physical, Biofilter, Bio mitigation

Introduction

Aquaculture has grown rapidly over the last few decades and has become one of the world's fastest-growing food production sectors. Today, aquaculture contributes more to the global supply of aquatic food than capture fisheries, helping to meet the increasing demand for fish and other seafood. This remarkable progress has been made possible through the successful cultivation of species such as tilapia, catfish, salmon, shrimp, seaweeds, and bivalves using well-developed and standardized farming techniques. As the demand for aquatic products continues to rise, farmers have adopted intensive culture practices such as high-density stocking, cage farming, and the use of nutritionally balanced pelleted feeds to increase production. While these methods improve productivity, they also generate considerable amounts of uneaten feed, fish faeces and other organic wastes. If these wastes are not managed properly, they can accumulate in the surrounding water, leading to poor water quality, disease outbreaks, environmental degradation, reduced farm productivity, and economic losses.

To address these challenges, the ecosystem approach to aquaculture has gained increasing importance. This approach focuses on making better use of natural resources by recycling nutrients and reducing waste, while promoting environmentally sustainable aquaculture. One of the most successful examples of this approach is Integrated Multi-Trophic Aquaculture (IMTA), where fed species such as fish are cultured together with extractive organisms like seaweeds, aquatic plants, and bivalves. Freshwater integration with recirculatory aquaculture system as well as with aquaponics has shown a new horizon towards bicircular economy and sustainable culture

approach. These organisms utilize the nutrients and organic wastes released by the cultured fish, thereby improving water quality, reducing environmental impacts, and enhancing the overall sustainability and productivity of the farming system.

Definition

“IMTA is a sustainable aquaculture practice that combines different aquaculture species at various trophic levels to utilize waste generated from one species as a nutrient for the other one.”

Genesis of the concept

1970: Ryther and co-workers created the modern, integrated, intensive, land mariculture and integration of extractive organisms like shellfish, microalgae, seaweeds in the experimental basis by using the domestic wastewater effluent mixed with seawater, which became a medium for plankton taken by the oysters as a food and finally the effluent filtered by seaweeds.

1976: Huguenin proposed method of treatment of wastewater effluents in both inland and coastal area. Tenor integrated that system for carnivorous fish and the macro agnivore abalone.

1977: Hughes and Games first used the marine fish, shellfish, phytoplankton culture which is followed by Gordin in 1981.

1989: Semi-Intensive seabreams & grey mullet pond system by the Gulf of Aqaba on the red sea which supported diatom population efficiently & feed the oyster in an excellent manner.

Recent advancements

2016-IMTA as a sustainability strategy: Greater emphasis on IMTA for reducing nutrient and organic matter discharge, using

extractive species as biofilters. Diversification to additional trophic levels was proposed.

2017-Technology transfer & commercialization: Research moved beyond experimental systems toward transferring IMTA technology to farms. Simplicity of system design and farmer adoption became important considerations.

2018-Offshore IMTA & regional development: Stronger interest in offshore IMTA, spatial arrangement and integration with marine cage systems. IMTA development was also demonstrated for tropical brackish water species in India.

2019-Optimization of species combinations: Greater attention to selecting complementary fed and extractive species, nutrient capture efficiency and appropriate biomass ratios.

2020-Economic sustainability: IMTA research increasingly examined profitability, market value, production diversification and economic feasibility, rather than environmental benefits alone.

2021-Circular nutrient recovery: Greater emphasis on treating aquaculture waste as a resource and improving nutrient recycling through multiple trophic components.

2022-System optimization & diversification: Increasing research on combining several extractive organisms—seaweeds, molluscs, echinoderms and other organisms—and optimizing system design.

2023-IMTA + RAS/Bio floc & freshwater applications: IMTA began to be increasingly discussed alongside RAS, bio floc, aquaponics and freshwater integrated systems. Tilapia and other freshwater species

were considered in closed-loop configuration.

2024-Performance, welfare & life-cycle assessment: Research expanded to fish growth, survival, feed efficiency, animal welfare and product quality, while Life Cycle Assessment (LCA) became an important tool for evaluating environmental sustainability.

2025-Circular economy & freshwater closed systems: Stronger focus on freshwater IMTA + RAS + hydroponics, water conservation, nutrient recovery and circular bioeconomy. Seaweed's role as an inorganic nutrient extractor was also extensively reviewed.

2026-Smart, cascade & highly integrated IMTA: Current direction is toward closed-loop/cascade IMTA, precision monitoring, multiple trophic levels, automation and resource-efficient systems. Recent work is also assessing environmental, economic and social sustainability together.

Concept of IMTA

IMTA system involves the use of two important words “integrated” which refers to intensive and synergistic cultivation, “Multitrophic” refers to the different trophic levels are being taken care of in this system. Mainly two types of organisms are incorporated for the culture purpose;

a) Fed species: The organisms which are cultured primarily i.e. large carnivorous species.

b) Extractive species: These are the species which utilizes the waste generated from the fed species. It is further divided into 2 groups.

- **Inorganic extractive species:** The organism which utilizes the dissolved inorganic matters like nitrogen & phosphorous.

- **Organic extractive species:** These organisms utilize the particulate waste generated in the system for their nutrient purpose.

Unlike a conventional polyculture system, this approach involves the cultivation of organisms belonging to different trophic levels. Although the cultured organisms share common biological and chemical processes within the system, the major emphasis is on utilizing the nutrients and energy generated at one trophic level by organisms at another. Thus, the system supports intensive production of multiple species through efficient nutrient recycling and energy transfer. The system utilizes more space in open water systems like cage culture whereas in closed systems like recirculatory aquaculture system (RAS), it needs to be more compactly placed.

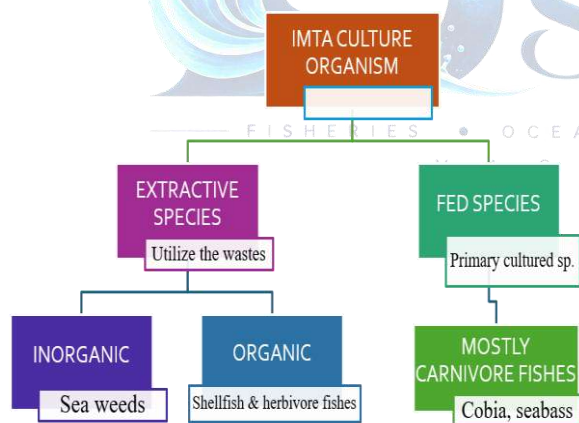


Fig: Components of IMTA

Different components of IMTA

A. Inorganic extractive sub-system in IMTA

In an Integrated Multi-Trophic Aquaculture (IMTA) system, the inorganic extractive component is mainly represented by seaweeds and other photosynthetic organisms. These organisms utilize dissolved

inorganic nutrients, particularly nitrogen and phosphorus, released from the culture of fed organisms such as fish. Thus, the autotrophic activity of seaweeds complements the heterotrophic processes associated with fish and microorganisms and contributes to maintaining a more balanced culture environment. Their incorporation into an IMTA system can reduce the nutrient load from intensive fish culture while also providing an additional harvestable crop. Moreover, seaweeds occupy a lower trophic level and obtain most of their nutrient requirements directly from the surrounding water, thereby requiring comparatively low external inputs for their cultivation. Several seaweed species, including *Kappaphycus alvarezii*, *Ulva* spp., *Gracilaria* spp., *Eucheuma* spp. and different kelp species, have been used or considered for integration into IMTA systems. Selection of a suitable seaweed species is important for achieving effective nutrient removal as well as obtaining an economically valuable secondary crop. The major criteria for selection include:

- High growth rate and capacity to accumulate nutrients, particularly nitrogen, in the tissues.
- Ease of cultivation, propagation and management of the life cycle under culture conditions.
- Resistance to epiphytes, diseases and other biological stresses.
- Compatibility of the eco-physiological requirements of the species with the prevailing environmental conditions of the culture site. Seaweeds with a high surface-area-to-volume ratio generally exhibit greater nutrient uptake potential.

- Preference for locally available species that do not pose a risk of becoming invasive or introducing pathogens into the culture environment.
- Adequate market demand and economic value of the harvested biomass.

One of the major challenges associated with seaweed-based nutrient extraction in open-water IMTA systems is the relatively low and variable nutrient-recovery efficiency. Water movement, dilution and the three-dimensional hydrodynamics of the culture area can rapidly disperse dissolved nutrients away from the seaweed component. Therefore, proper spatial arrangement of the cultured organisms, site-specific hydrodynamic assessment and modelling of nutrient transport are important areas requiring further research for improving the efficiency of open-water IMTA systems.

B. Organic extractive species sub-system in IMTA

In an IMTA system, organic extractive organisms such as bivalves are generally cultured in close proximity to fish cages or other fed components. These filter-feeding organisms utilize suspended particulate matter, including uneaten feed, faecal particles and plankton, thereby helping to reduce the organic load in the surrounding water. At the same time, the assimilated nutrients are converted into bivalve biomass, providing an additional harvestable product from the system. Selection of a suitable bivalve species is important for improving the efficiency of organic waste utilization. The major criteria for selection include:

- Knowledge of the size and nature of particulate wastes generated from the fed component of the IMTA system, so that a bivalve species capable of efficiently

filtering the available particles can be selected.

- Feeding behaviour and interaction of the filter-feeding species with the surrounding culture environment.
- Filtration and nutrient uptake capacity of the selected bivalve species.
- Ability to grow efficiently under the prevailing environmental conditions of the culture site.
- Commercial value and market acceptance of the harvested species.

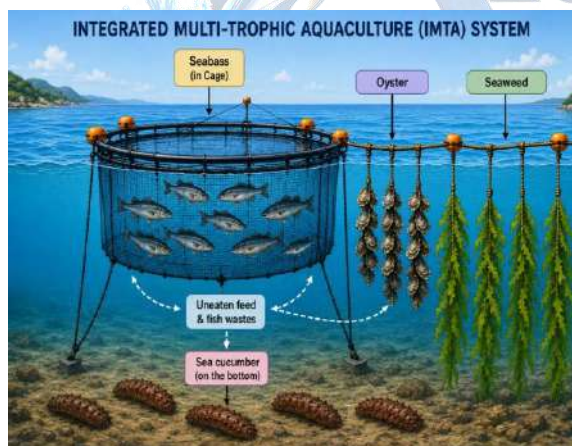
In some cases, marketability of the secondary extractive species may limit the economic performance of the system. Therefore, more than one extractive component may be incorporated at different stages of nutrient recovery. Suitable fish or other organisms may utilize larger organic particles close to the primary fed species, whereas bivalves can serve as a subsequent bio-filter by removing finer suspended particles from the water column. Commercially important bivalves such as the green mussel *Perna viridis* and the Indian backwater oyster *Magallana bilineata* (formerly *Crassostrea madrasensis*) can be integrated with fed aquaculture systems along the Indian coast. Their incorporation may contribute to the recovery of particulate organic nutrients, reduction of localized nutrient enrichment and generation of an additional economically useful crop.

C. Fed aquaculture sub-system in IMTA

The fed aquaculture component of an IMTA system is generally represented by finfish or other organisms that depend on externally supplied feed. This component serves as the primary source of nutrients within the system. During culture, a portion of the

supplied feed is released into the surrounding environment in the form of uneaten feed, faecal matter and dissolved metabolic wastes. These nutrient-rich outputs subsequently become available to the organic and inorganic extractive components of the IMTA system.

The quantity and composition of the wastes generated from the fed component depend on several factors, including the cultured species, stocking biomass, size of the organisms, feeding rate, feed composition and digestibility. Therefore, appropriate feed management and selection of compatible extractive species are essential for achieving effective nutrient utilization. Besides supporting nutrient transfer within the IMTA system, the fed species generally constitute the principal commercial crop and contribute substantially to the overall economic return of the production system.



Design of IMTA

The establishment and smooth operation of an efficient system depend on the organized assembling of all the components for the proper collection of all the waste generated in the system and its efficient utilization. For example, in a system model consists of a seabass culture unit, oysters, seaweeds, each performing a specific ecological function.

Seabass is cultured in a cage and fed with formulated feed, generating organic and inorganic wastes. Oysters, functioning as filter feeders, are placed near the fish cage to utilize suspended organic particles and improve water quality. Seaweeds are cultured on ropes around the culture unit and absorb dissolved nutrients, particularly nitrogen and phosphorus, released from fish wastes. Sea cucumbers are positioned at the bottom of the system, where they consume deposited organic matter and sediments. Thus, the model represents the flow and recycling of nutrients among different components, where the waste generated by one trophic group becomes a resource for another. The integration of these species helps reduce nutrient accumulation, improve water quality, enhance resource utilization, diversify aquaculture production, and minimize environmental impacts. Overall, the IMTA model illustrates the principle of “waste as a resource” and demonstrates how different aquatic organisms can be integrated to develop a more productive, balanced, and sustainable aquaculture system.

Transition towards freshwater IMTA

Freshwater IMTA replaces marine extractive species with organisms capable of utilizing nutrients under freshwater conditions. Depending on the system, combinations may include tilapia, carp or catfish as fed species; freshwater mussels and prawns/crayfish as consumers of particulate or organic material; and aquatic plants, microalgae or hydroponic crops as nutrient extractors. The fundamental principle remains the same: nutrients released through uneaten feed, faeces and metabolic excretion are redirected toward the production of additional biomass rather than being discharged as waste.

a. Integration with closed/RAS systems

The development of RAS has provided an important technological platform for freshwater IMTA. In a closed IMTA-RAS, water is continuously circulated between the different production and treatment components. A typical pathway is:

Fish culture → solids collection → biofiltration → microbial conversion → extractive organisms/plants → final water treatment → fish culture

This differs from open-water IMTA because the system has substantially greater control over water flow, nutrient concentration, hydraulic retention time, dissolved oxygen, temperature and biosecurity.

b. Emergence of IMTA-aquaponics integration

A particularly important recent advancement is the combination of freshwater IMTA with aquaponics/hydroponics. Rather than relying exclusively on aquatic extractive organisms, plants can act as additional nutrient sinks. This creates a more complete nutrient-recovery pathway:

Fish → organic/inorganic waste → microbial transformation → nitrate/phosphate → plants → harvested biomass



Benefits

- Biomitigation of aquaculture effluents: Extractive species utilize dissolved and particulate wastes generated from the fed component, thereby reducing the nutrient load released into the surrounding environment.
- Higher income through diversification: Production of more than one commercially valuable species provides additional sources of revenue from the same farming system.
- Support to the local economy: Diversified production can generate employment and create opportunities for processing, marketing and other associated activities.
- Natural crop insurance: Cultivation of species belonging to different trophic levels reduces complete dependence on a single crop and can partly compensate for losses if the performance or market value of one species declines.
- Improved environmental and health management: Better utilization of organic and inorganic wastes may improve the culture environment and, under suitable management, help reduce stress and disease risks.
- Possibility of premium pricing: Environmentally responsible production may provide scope for product differentiation through eco-labelling, sustainability certification or suitable organic certification programmes.

Challenges

- Higher initial investment: Establishment of an IMTA system may require additional infrastructure, culture units and management inputs.
- Complex farm coordination: Simultaneous management of organisms

belonging to different trophic levels requires greater technical knowledge and operational planning.

- Larger spatial requirement: Integration of multiple culture components may require more farming area than a conventional monoculture system.
- Policy and leasing constraints: Adoption of open-water IMTA can be difficult in regions where suitable leasing, licensing and regulatory provisions are not available.
- Limited availability of compatible species: Selection of species with appropriate feeding habits, environmental requirements, growth performance and market demand can be challenging.
- Food safety concerns: Extractive species may accumulate undesirable microorganisms, contaminants or toxic substances from the surrounding environment; therefore, proper site selection, monitoring and food-safety assessment are essential.

Conclusion

IMTA offers an effective approach for reducing both inorganic and organic nutrient loading in open-water as well as confined aquaculture systems, thereby contributing to better environmental management and ecological balance. By integrating species from different trophic levels, the system promotes more efficient utilization of nutrients and can also provide additional sources of income to coastal and inland fish

farmers. A major development in the concept of IMTA is that closed freshwater systems are no longer considered merely as a means of treating aquaculture wastes. Instead, they are increasingly viewed as resource-recovery systems in which nutrients such as nitrogen, phosphorus and carbon, which would otherwise be lost from the production system, can be captured and converted into additional marketable biomass. This approach is closely associated with the principles of circular bioeconomy and improved resource-use efficiency. With appropriate species selection, system design and management, IMTA also has the potential to contribute towards climate-resilient aquaculture by reducing nutrient losses, improving resource utilization and diversifying production. Its possible role in carbon sequestration and carbon-credit mechanisms is also receiving increasing attention, although such benefits require proper quantification and verification before being considered for carbon-credit generation.

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Understanding Harmful Algal Blooms: Causes, Impacts and Control Measures

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ABSTRACT

Algal blooms are rapid, excessive growth of phytoplankton, which is an escalating threat to aquatic ecosystems, coastal economies, and public health, driven by anthropogenic nutrient enrichment and changing climatic scenarios. This ephemeral phenomenon can trigger a cascade of adverse impacts, such as toxin production, oxygen depletion in water bodies, massive mortalities of aquatic organisms, food chain disruption and even huge economic losses exceeding billions of dollars through aquaculture devastation, tourism decline and drinking water contamination. Toxin-producing species such as cyanobacteria, diatoms, and dinoflagellates further accelerate mortality through neurotoxins and cytotoxic compounds that often lead to marine shellfish poisoning in humans. The control of HABs spans physical, chemical, and biological methods, each with distinct advantages and limitations. HABs remain a growing and multifaceted threat, which can lead to a cascade of events like ecosystem disruption, human poisoning and huge annual economic losses, so effective management requires moving beyond a single method approach and using integrated systems combining preventive and curative measures across aquatic ecosystems.

KEYWORDS

Eutrophication, Harmful Algal Bloom, Nutrients, Toxins, Climate Change

Introduction

Algal blooms are dense aggregations of phytoplankton cells of one or more species, manifesting as noticeable changes in water discolouration, foam production, and eventually invertebrate mortality or toxicity to humans (Padmakumar, Menon and Sanjeevan, 2012). Algal blooms are a rapid, ephemeral phenomenon when phytoplankton assemblages exceed their mortality rates in both freshwater and marine aquatic habitats. Blooms cause prominent discolouration in water owing to the presence of pigments, appearing as brown, red, mahogany, or green tides, which float on the surface in scums and cover beaches with biomass, exudates or foam. Blooms that can cause injury to animals or the ecology by producing toxins, depleting oxygen in water bodies, disrupting the ecosystems or interfering human activities, and contaminating drinking water regardless of the concentration, are called "harmful algal blooms" (HAB) (Feng *et al.*, 2024; Brenckman *et al.*, 2025). The blooms of these organisms are attributed to two primary factors: anthropogenic factors like nutrient enrichment, leading to eutrophication and natural processes, such as circulation, upwelling relaxation, and river flow. Their global occurrence has substantially increased since the 1980s, including a 44% increase from the 2000s to the 2010s, particularly in Asia and Africa (Feng *et al.*, 2024).

Causes of harmful algal bloom

Harmful algal blooms are caused by environmental conditions such as nutrient enrichment, water temperature, light availability, and water column stratification

(Lan *et al.*, 2024). The frequency, duration, and geographic extent of these blooms are primarily driven by anthropogenic nutrient enrichment and climate change (Brenckman *et al.*, 2025). Nutrient loading causes excessive phytoplankton development, high levels of chlorophyll, decreased biodiversity, and decreased water quality, and even high amounts of bacteria, scums, fungi, hypoxia, and ultimately anoxia are seen in more advanced phases (Kitsiou & Karydis, 2011). Agricultural runoff, waste water discharge, and industrial pollution introduce nitrogen, phosphorus, and silica, promoting bloom formation (Lim *et al.*, 2023). Climate change exacerbates this problem by altering precipitation patterns, increasing water temperature, and intensifying coastal upwelling, all of which are factors favouring algal proliferation (Brenckman *et al.*, 2025). Table 1 enlists the causes of harmful algal blooms

Table 1 Causes of harmful algal bloom

Factor		Details
	Nutrients	Runoff from agriculture, stormwater, road, and sewage, including point sources such as sewage and confined animal feed operation discharges. Atmospheric deposition and upwelling of ocean water. Nitrogen (N), Phosphorus (P), and Silicon (Si) are the primary nutrients

	Environmental conditions	Higher light intensities and rising temperature promote algal growth. Temperature is a key factor as it influences growth rate, toxin production, duration and species composition
	Seasonal factors	Warm water conditions (autumn and late summer) promote algal bloom
	Hydrodynamic factors	Moderate water turbulence, slow flow velocity, and stratification of the water column support algal growth. Clear water, as in reservoirs, lakes, quarries slow moving rivers, provides ideal habitat
	Climate change	Increase in water and air temperature, increases in droughts and flooding, changes in salinity, Higher atmospheric and aquatic CO ₂ concentrations, Ocean Acidification, sea level rise and coastal upwelling favour algal growth

Impacts

According to Hallegraeff (2003), there are three main categories of HAB-causing microorganisms. (1) Non-toxin-secreting species that alter the recreational value of the area by causing discoloration of the water or producing enormous amounts of foam, or cause high rates of fish mortality

via the drastic reduction of dissolved oxygen in water, due to the explosive increase in microalgal cell density; (2) Species that are not toxic to humans but affect the inhabiting fish by physically injuring the fish, for example, by obstructing their gills and/or by the production of ichthyotoxic substances; and (3) toxin-producing species can cause a range of neurological and gastrointestinal disorders through their uptake by the food chain. HAB can cause adverse impacts through two major mechanisms: toxin production and high biomass and organic matter production. The death and decomposition of bloom biomass depletes dissolved oxygen, creating hypoxic dead zones where aquatic organisms cannot survive (Hallegraeff, 2003; Messineo et al., 2024). Figure 1 illustrates the detrimental impacts of HABs. Toxin-producing species contaminate seafood and drinking water, causing increased water treatment costs and public health concerns due to various biotoxins. Beyond the risks of ingestion, the effects of HAB-derived toxins on human health include allergies, skin reactions, respiratory irritation, and potential long-term carcinogenic associations (Messineo et al., 2024). Cyanobacteria dominate freshwater habitats, producing microcystin and nodularin, which affect drinking water quality and tourism. Dinoflagellates and diatoms are two diverse categories of algae that are predominantly seen in marine habitats and are responsible for causing red tides and producing biotoxins, including Brevetoxin, azaspiracid, ciguater toxins, okadaic acid, saxitoxin, and domoic acid, causing neurotoxic shellfish poisoning (NSP), Azaspiracid Shellfish Poisoning (AZP), Ciguatera Fish Poisoning (CFP), Diarrhetic Shellfish Poisoning (DSP), Paralytic Shellfish Poisoning (PSP), and Amnesic Shellfish Poisoning (ASP) in humans (Van

Dolah, 2000). These blooms can contaminate seafood, causing bans on fishery products and exports, and causing economic losses for fisheries (Hallegraeff, 2003). HABs can trigger huge economic losses exceeding billions of dollars annually through aquaculture devastation, tourism decline, loss of recreational values, and drinking water contamination. HABs cause serious ecological consequences, such as a decrease in biodiversity, loss of seagrass, coral bleaching, and fish and mammal mortality. HABs alter the trophic dynamics in aquatic environments by disrupting food web structures in several ways. For instance, due to nutrient enrichment, traditional primary consumers, such as zooplankton, are frequently outcompeted by HABs, which eventually causes a food web disruption and decrease in biodiversity. Phytoplankton serves as the base of the majority of marine food webs that provide provisional ecosystem services while also being a contributor of excess organic matter, often resulting in coastal eutrophication. A change in the species makeup of phytoplankton can aid in the prolific growth of detrimental algae and cause depletion of oxygen in water due to decomposition and can cause mass fish mortality and ecological collapse (Diaz et al., 2008).

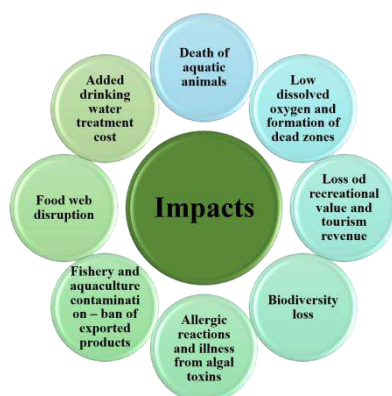


Figure 1 : Impacts of harmful algal bloom

Detection of algal blooms

Satellite remote sensing, molecular biotechnology, and machine learning-driven predictive models are integrated for effective algal biomass monitoring. Conventionally, algal bloom in a water body can be estimated in three ways, including quantifying chlorophyll a (CHL a), measuring carbon biomass, or by measuring the particulate organic carbon (POC) in a sample. In addition, analytical techniques like bioassays, biosensors, HPLC, LCMS, and continuous monitoring using sonde buoys and even portable algal bloom detectors like chlorophyll metres are also used for this purpose (Brenckman et al., 2025b).

Control measures and management

For the control of algal blooms, mechanical, biological, chemical, genetic and environmental control measures can be utilized (Anderson, 2009; Song et al., 2023). Physical methods include manual removal and other methods such as filtration, skimming, electrolysis, and water mixing, which can be performed using mechanical (pumps), hydraulic, or pneumatic mixers. Also, use of floating covers can avoid the proliferation of photosynthetic organisms. Methods such as ultraviolet radiation, centrifugal separation, magnetic separation, and air flotation are constrained by high energy costs and limited scalability to large water bodies (Zeng et al., 2023). Adding clay particles or flocculants controls algae, which helps to carry blooms to bottom sediments, but it raises certain environmental concerns. Another physical method is to pump out the surface algal

scums or blooms from lakes. Aeration and mixing are expensive, but effective and environmentally friendly algal control methods that maintain and refresh water bodies. Mechanical aeration leads to the reduction of algal growth by mixing algae deeper into the water column and starving them of light. In addition, it is also used to prevent and reduce the sediment phosphorus load available to the water column by decreasing the likelihood of anoxia. Ultrasound methods are also used to mitigate HAB and it works by a phenomenon known as acoustic cavitation, which occurs when sound waves of over 20 kHz travel through a liquid medium. A sound layer is created in the top layer of water by ultrasound waves and damage the buoyancy of the algal cells directly, causing them to sink to the bottom, where they are unable to photosynthesise due to a lack of light and dies eventually (Park et al., 2017).

Biological control agents, such as fish, bacteria, phage and fungi, which are used to control blooms (Anabtawi et al., 2024). The primary source of food for herbivorous fish are algae, and algal growth can be controlled by stocking fish such as tilapia and grass carp. *Microcystis aeruginosa*, a bloom forming algae, are removed by grazing on them by species such as bighead (Aristichthys nobilis), silver carp (*Hypophthalmichthys molitrix*), and freshwater mussel (*Hyriopsis cumingii*). Furthermore, bacterial secretions such as cyanobacterial substances and secondary metabolites, which release mucous-like secretions for self-defence and utilize entrapment techniques with antagonistic volatiles is also found useful for bloom control. Zooplanktons, such as cyclopoid copepods and calanoids,

reduce the cyanobacterial load in water by grazing on them. Algae are also used as a control agent in the bio-flocculation method, which involves the mediation of flocculants in the presence of microorganisms or the release of biodegradable macromolecular flocculants by microorganism (Yang et al., 2024). Biocontrol methods are eco-friendly, contamination-free, and low-cost removal strategy, but it has certain practical limitations and will not function at oxygen-poor conditions.



Figure 2: Chemical agents used for control of algal bloom

Algal blooms can be eliminated using chemical agents such as copper sulfate, triosyn, hydrogen peroxide, flocculants, and herbicides, which act rapidly and at low cost (Figure 2). However, algaecide-induced cell lysis releases intracellular toxins into water, creating secondary pollution (Anabtawi et al., 2024) (Kim et al., 2007). Hydrogen peroxide (H_2O_2) is a recommended and effective method for lysing cyanobacteria in lakes and ponds. In comparison, H_2O_2 price is low, has low toxicity for non-target species, and is selective among chemicals. Another method is the use of decomposed barley straw to control algae and cyanobacteria. Flocculants bind and settle the available phosphorous in the system, which leads to reduced phytoplankton growth. Flocculants such as sodium aluminate, aluminium sulfate, native clays, chitosan, and phoslock (lanthanum clay) prevent harmful algal blooms by controlling phosphorus levels (Sengco and Anderson, 2004; Lurling and Oosterhout, 2013).

Bioremediation, nutrient load reduction, and regulatory policies are the backbone of sustainable management. Responsible agricultural practices and waste reduction can be promoted by public awareness and community involvement. Artificial wetlands or pre-reservoirs upstream of water storage can be utilized as nutrient sinks which prevents the inflow of nutrients into storage. Planting trees and shrubs around a water body reduces the input of sediments and, therefore, nutrients into the water body. In addition, plants also provide shade to water bodies, which reduces the temperature and solar radiation reaching the water body. Managing whole catchment above the storage by reducing the use of fertilisers and

fencing off waterways to prevent stock access will also reduce soil erosion and amount of nutrients.

Conclusion

Harmful Algal Blooms are a global crisis driven by a dangerous mix of climate change, damaged environments and nutrient pollution in our waters. Tackling this problem requires teamwork, better technologies, and stronger environmental laws. There is an obvious need to comprehend HAB occurrences and create scientifically sound management and mitigation strategies as the world's population is growing, increasing the use of the coastal zone and demanding additional fisheries and recreational resources. Over the past 20 years, algal and toxin monitoring systems have been established worldwide, and this data should help us spot long-term trends and understand how these blooms shift from year to year. In this sense, research advancements are essential, driven by worldwide collaboration and coordination.

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Molecular Techniques in Diagnostic Pathology of Fish: A New Era in Aquatic Animal Health Management

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ABSTRACT

The intensification of aquaculture has increased the risk of infectious diseases, creating a need for rapid and reliable diagnostic tools. Molecular techniques have transformed fish disease diagnosis by enabling sensitive and specific pathogen detection, often before clinical signs appear. This article reviews major approaches, including PCR, qPCR, ddPCR, LAMP, RPA, RAA, ERA, CRISPR-based diagnostics, DNA barcoding, FISH and molecular biosensors, highlighting their applications, advantages and limitations in aquatic animal health management. Particular emphasis is placed on the integration of isothermal amplification with CRISPR and portable detection platforms for rapid, field-deployable diagnosis. Emerging technologies such as nanopore sequencing, eDNA, metagenomics, lab-on-a-chip and smartphone-assisted diagnostics offer further opportunities for real-time disease surveillance. Despite challenges related to cost, standardization and field validation, continued advances in portable and affordable molecular diagnostics are expected to strengthen biosecurity, disease management and sustainable aquaculture.

KEYWORDS

Fish pathology; Molecular diagnostics; Aquatic animal health; CRISPR-based diagnostics; Isothermal amplification.

Introduction

Aquaculture is one of the fastest growing food production sectors worldwide with an average annual growth rate of 5.1% (FAO, 2026). However, the rapid intensification of aquaculture has increased the occurrence of infectious diseases caused by bacteria, viruses, fungi and parasites, leading to significant economic losses and threatening sustainable production. To prevent these losses conventional diagnostic methods such as clinical examination, microscopy, histopathology and biochemical assays, remain important but are often labour intensive, time consuming and less sensitive for detecting pathogens during the early stages of infection (Jaies *et al.*, 2024). Recent advances in molecular biology have revolutionized fish diagnostic pathology by enabling rapid, highly sensitive and specific detection of pathogens.

This article highlights the major molecular diagnostic tools used in fish pathology, their applications, advantages, challenges and emerging innovations that are shaping the future of aquatic animal health management.

How Molecular Diagnostics Works?

Molecular diagnosis identifies disease-causing organisms by detecting their unique genetic material (DNA or RNA) in fish tissues, body fluids or environmental samples. The process begins with sample collection from infected fish by collecting swabs from anterior kidney, buccal area, eye, liver, spleen and lower intestine (Shahi *et al.*, 2018) and their culture or preservation in suitable media. Nucleic acids are then extracted and amplified using molecular techniques such as PCR, LAMP or RPA to increase the amount of target genetic material. The amplified products are subsequently detected through fluorescence, gel electrophoresis, lateral-flow strips, sequencing or biosensor based platforms to confirm the presence of specific pathogens.

Targeting Fish Pathogens with Specific Primers

For detecting a pathogen, specific primers are designed to target unique genetic regions. The choice of target gene depends on

the pathogen and the objective of the assay. For bacterial pathogens, conserved genes such as *16S rRNA*, *gyrB*, *groEL* and virulence-associated genes (e.g., *aerA* of *Aeromonas hydrophila*) are commonly targeted, while viral assays amplify specific genomic regions having high conserved score are targeted. For example, in Indian isolates of Tilapia Lake Virus (TiLV) segment 6 have a high conserve score of 97.58 (Thangadurai *et al.*, 2026) showing a high potential of target gene for developing a primer. Careful primer design minimizes non-specific amplification and enhances the sensitivity and specificity of molecular assays, enabling early and reliable detection of fish pathogens.

Table1. Characteristics of an Ideal PCR Primer

Parameter	Recommended Value
Primer length	18–30 nucleotides
GC content	40–60%
Melting temperature	55–65°C
Amplicon size	100–500 bp (diagnostic PCR)
Secondary structures	Avoid hairpins and dimers
Specificity	Target pathogen-specific gene

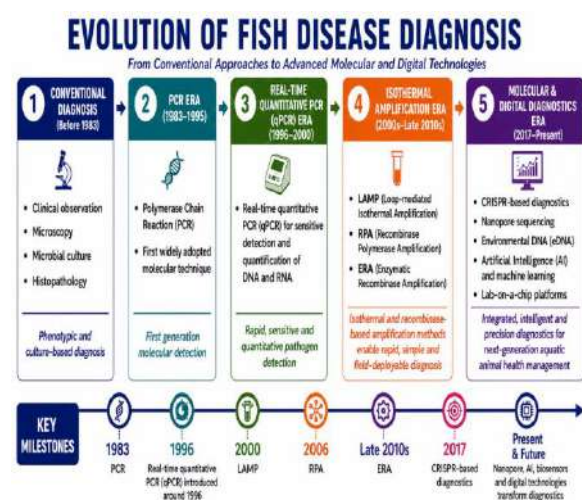


Figure 1: Diagrammatic representation of evolution of disease diagnosis in fish

Major Molecular Diagnostic Tools Used in Fish Pathology

1. Polymerase Chain Reaction (PCR)

Polymerase chain reaction (PCR) is the foundation of molecular diagnostics in fish pathology. It amplifies specific DNA sequences and offers high sensitivity and specificity. Its application can be extended to reverse transcription PCR for the RNA viruses by converting viral RNA into complementary DNA (cDNA) before amplification. It is widely used for diagnosing Tilapia Lake Virus (TiLV), Viral Nervous Necrosis Virus (VNNV) and Infectious Salmon Anaemia Virus (ISAV), providing reliable confirmation but the process is time consuming, requires a thermal cycler and well equipped laboratory.

2. Quantitative PCR (qPCR)

Quantitative PCR (qPCR), also known as real-time PCR, combines amplification with fluorescent detection to quantify pathogen load. Besides confirming infection, qPCR helps monitor disease progression, evaluate treatment efficacy and detect pathogens before clinical signs appear, making it a preferred tool for disease surveillance programmes.

3. Droplet Digital PCR (ddPCR)

Droplet digital PCR (ddPCR) partitions a sample into thousands of microscopic droplets, allowing absolute quantification of nucleic acids without requiring standard curves. Its exceptional sensitivity makes it valuable for detecting low-copy pathogens, latent infections and carrier fish that may escape conventional PCR detection.

4. Loop-Mediated Isothermal Amplification (LAMP)

Loop-mediated isothermal amplification (LAMP) amplifies DNA under a constant temperature (60–65°C), eliminating the need for a thermal cycler. Results are generated within an hour and can often be interpreted visually through colour changes. Because of its simplicity and affordability, LAMP has become an attractive tool for rapid diagnosis of diseases caused by *Aeromonas hydrophila*, KHV and

Streptococcus spp. in hatcheries and fish farms (Rolando et al., 2024).

5. Recombinase Polymerase Amplification (RPA)

Recombinase polymerase amplification (RPA) is another isothermal technique that operates at relatively low temperatures (37–42°C) and produces results within 20–30 minutes. Its portability and rapid turnaround make RPA highly suitable for on-site diagnosis, particularly when combined with portable detection devices (Bohara et al., 2024).

6. CRISPR-Based Diagnostics

CRISPR-Cas systems was originally developed for genome editing but in recent years have emerged as next-generation diagnostic platforms. Cas12 and Cas13 enzymes recognize pathogen specific nucleic acids with remarkable precision and generate detectable fluorescent or lateral flow signals. When integrated with LAMP or RPA, CRISPR assays provide ultra-sensitive, rapid and field deployable diagnostics for emerging fish diseases (Sahalet al., 2024).

Table 2. Molecular diagnostic techniques used for disease diagnosis in aquaculture

Technique	Target	Time Required	Sensitivity	Equipment Required
PCR	DNA	3–4 h	High	Thermal cycler
Reverse Transcriptase-PCR	RNA	3–4 h	High	Thermal cycler
qPCR	DNA/RNA	1.5–2 h	Very High	Real-time PCR system
ddPCR	DNA/RNA	3–4 h	Extremely High	Droplet digital PCR system
LAMP	DNA	30–60 min	High	Heating block/water bath
RPA	DNA/RNA	15–30 min	High	Portable incubator
CRISPR-Cas	DNA/RNA	30–60 min	Very High	Portable detection platform

7. Recombinase-Aided Amplification (RAA)

Recombinase-Aided Amplification (RAA) employs recombinase proteins to facilitate primer binding to homologous target DNA, followed by strand displacement and amplification at a constant temperature of 37–42°C. The assay provides results within 15–30 minutes with high sensitivity and specificity. RAA has been applied for detecting bacterial and viral pathogens in aquaculture, enabling early disease diagnosis. Its simple operation, minimal equipment requirement and compatibility with portable detection devices make RAA particularly suitable for on-site disease surveillance in fish farms.

8. Enzymatic Recombinase Amplification (ERA)

Enzymatic Recombinase Amplification (ERA) is an improved recombinase based isothermal amplification method designed to enhance reaction efficiency and robustness. By optimizing the enzyme formulation, ERA enables rapid amplification of target nucleic acids with excellent sensitivity under constant temperature conditions. Recent development of One pot ERA-CRISPR/Cas12a based rapid diagnostic kit for *Lactococcus garvieae* (Wang et al., 2026) is one of the example of increasingly — coupled ERA-CRISPR-Cas

9. DNA Barcoding

DNA barcoding uses conserved genetic markers such as the cytochrome c oxidase subunit I (COI) and 16S rRNA genes to accurately identify fish species, parasites and seafood products. It also supports biodiversity assessment, species authentication and traceability within fisheries and aquaculture.

10. Fluorescence In Situ Hybridization (FISH)

Fluorescence in situ hybridization (FISH) combines molecular biology with histopathology by using fluorescent probes that bind directly to pathogen nucleic acids within infected tissues. This technique simultaneously visualizes pathogens and associated tissue

damage, thereby improving diagnostic accuracy and understanding of disease pathology (Jaies et al., 2024).

11. Molecular Biosensors

Recent advances have led to the development of electrochemical, optical, hydrogel and CRISPR integrated biosensors capable of detecting pathogens within minutes. These portable platforms require minimal sample preparation and have great potential for real-time disease monitoring directly at aquaculture farms (Bohara et al., 2024).

Advantages of Molecular Diagnostics

Laboratory-based techniques such as PCR, RT-PCR, qPCR, ddPCR and DNA sequencing remain the gold standard for confirmatory diagnosis due to their high analytical accuracy and comprehensive data output. In contrast, field-deployable technologies including LAMP, RPA, CRISPR-based assays and molecular biosensors offer rapid, affordable and user-friendly diagnosis with minimal equipment. Recent advances have enabled the integration of multiple technologies, such as LAMP-CRISPR, RPA-CRISPR and RPA-lateral flow assays, to enhance diagnostic accuracy, speed and portability.



Figure 2: Diverse Applications of Molecular Diagnostics in Fish Pathology
Challenges Associated with Molecular Diagnostics in Aquaculture

Despite their remarkable advantages, molecular diagnostic techniques face several challenges that limit their widespread adoption in aquaculture. Advanced platforms such as qPCR, ddPCR and next-generation sequencing require expensive instruments, costly reagents and skilled personnel, making them inaccessible to many small scale laboratories and fish farms,

particularly in developing countries. Diagnostic accuracy can also be compromised by contamination, improper sample handling and the absence of standardized protocols across laboratories. Furthermore, many molecular assays require validation under diverse field conditions before routine application, while regulatory approval and quality assurance remain important concerns.

Future Perspectives

The future of fish disease diagnostics lies in the integration of advanced molecular technologies with digital aquaculture. The digital revolution in aquaculture, fuelled by new technologies such as IoT sensors and AI-based systems, has huge potential (Bardola and Khati, 2024) which can be supplemented with CRISPR-based diagnostics, nanopore sequencing, lab-on-a-chip devices and smartphone assisted platforms to deliver rapid, portable and point of care pathogen detection. Simultaneously, integrated biosensors, environmental DNA (eDNA) monitoring and metagenomics enabled surveillance will facilitate real-time disease monitoring, predictive outbreak analysis and precision health management. Together, these innovations will enhance biosecurity, reduce production losses and accelerate the transition toward sustainable and precision aquaculture over the coming decade.

Conclusion

Molecular diagnostic technologies have fundamentally transformed fish pathology. Beyond improving diagnostic accuracy, these tools support proactive disease management through early detection, effective surveillance, enhanced biosecurity and informed health interventions, thereby reducing production losses and improving aquaculture sustainability. As emerging diseases, climate change and global trade continue to challenge aquatic animal health, integrating molecular diagnostics into routine monitoring programmes has become increasingly important. The convergence of molecular techniques with innovations will further enhance real time disease detection and decision making. Continued investment in affordable, field deployable diagnostic

platforms, standardized protocols and capacity building will accelerate their adoption worldwide. By strengthening aquatic animal health management, molecular diagnostics will play a pivotal role in ensuring sustainable aquaculture, protecting aquatic biodiversity and contributing to global food and nutritional security.

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Tracking the Gentle Giant: Whale Shark Conservation through Satellite Science

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ABSTRACT

The whale shark (*Rhincodon typus*), the world's largest fish, has become a flagship species for global marine conservation owing to its immense size, filter-feeding ecology, and gentle behaviour toward humans. Despite its charismatic status, the species has been classified as Endangered on the IUCN Red List since 2016, with the Indo-Pacific population estimated to have declined by 50–79%. Historical targeted fishing, bycatch in tuna fisheries, illegal trade in fins and liver oil, plastic pollution, and vessel strikes continue to threaten the species, even as international protections under CITES and CMS have expanded. Over the past decade, satellite-tracking research in Indonesia's Bird's Head Seascape and Coral Triangle has tagged more than 70 individuals, revealing that whale sharks cross at least 13 national maritime boundaries and spend substantial portions of their lives in international waters beyond the reach of any single nation's protection. Long-term photo-identification work in Mozambique, by contrast, has documented an alarming and unexplained decline exceeding 85% at a once-thriving aggregation site, underscoring that cessation of direct fishing does not guarantee recovery. Emerging tools biologging cameras, citizen-science photo-matching, and artificial intelligence are expanding understanding of whale shark behaviour and movement. This review synthesises recent findings on whale shark population status, threats, and tracking research, and argues that effective long-term conservation must extend beyond isolated marine protected areas to encompass migratory corridors, high-seas governance, and sustained collaboration with local fishing communities.

KEYWORDS

Whale shark; *Rhincodon typus*; satellite tracking; marine conservation; Indo-Pacific; endangered species; bycatch; CITES

Introduction

On a warm morning in Cenderawasih Bay, Indonesia, a fisherman lowers his bagan lift-net into the sea and waits for the catch. After some time, a large shadow, almost the size of a school bus, moves beneath the fishing platform. The animal is not dangerous; instead, its presence is considered a good sign by local fishers. Fishers in this region have long known that whale sharks often approach their nets to feed on anchovies that escape from them. This close relationship between local fishermen and whale sharks has become an important part of marine conservation research, helping scientists collect valuable information about *Rhincodon typus*, the largest fish species in the world (Himawan et al., 2015; Meyers et al., 2020).

The whale shark is well known for its extraordinary size. Some individuals have been reliably recorded at nearly 19 metres in length, making it the largest living fish and the largest non-mammalian animal on Earth (Compagno, 2001; Rowat & Brooks, 2012). Despite this size, the whale shark is a filter-feeding animal, filtering plankton, fish eggs, krill and small schooling fishes from seawater through its specialised gill structures, processing thousands of litres of seawater every hour (Motta et al., 2010; Rowat & Brooks, 2012). Its calm, harmless nature draws divers and tourists worldwide, making it an important flagship species for marine conservation (Gallagher & Hammerschlag, 2011; Rowat & Brooks, 2012) and supporting tourism economies in the Philippines, Mexico and Western Australia.

However, the whale shark also illustrates how populations of large marine animals can decline over time. Whale sharks are believed to live for more than 100 years, grow slowly, mature late, and reproduce at a low rate, making population recovery extremely slow after declines (Pierce & Norman, 2016; Rigby et al., 2019). Identifying the

major causes of population decline and prioritising conservation actions have therefore become central concerns in marine megafauna conservation research.

A Species Assessed as Endangered

The whale shark has been classified as Endangered on the IUCN Red List of Threatened Species since 2016, a status maintained in the latest assessment (Pierce & Norman, 2016; Rigby et al., 2019). Globally, the population is estimated to have declined by at least 50% over the last three generations a period that, depending on the generation length used, may represent approximately 75–120 years. The level of decline, however, is not uniform across regions. The Indo-Pacific region, home to a major share of the global population, has experienced a particularly severe decline of about 50–79%, driven by historical targeted fishing, accidental capture, and mounting pressure on key habitats. The Atlantic population, by comparison, has declined less and remains categorised as Vulnerable, though its trend continues to be a concern (Rigby et al., 2019). Whale sharks are currently protected under several international agreements. The species has been listed in Appendix II of CITES since 2002, regulating international commercial trade in whale shark products (CITES, 2002), and in Appendix II of CMS, with some populations in Appendix I reflecting the long migratory distances whale sharks travel between national waters (CMS, 2017; Pierce & Norman, 2016).

More than 45 countries have introduced national laws prohibiting the capture or trade of whale sharks, yet these measures have not eliminated threats. A proposal submitted before the 2025 CITES Conference of the Parties (CoP20) highlighted continuing problems such as illegal retention of bycaught whale sharks, trade in fins, liver oil and meat in parts of Asia, and increasing mortality from vessel collisions,

recommending that the species be transferred to the stricter Appendix I (CITES, 2025).

The Threats Converging on the World's Biggest Fish

For much of the twentieth century, direct fishing was the principal threat to whale sharks. Fisheries in the Philippines, Taiwan, India and the Maldives targeted the species for meat, fins and liver oil the latter valued as a source of squalene once common in cosmetics and supplements. Although many of these fisheries have since been closed or restricted, illegal fishing and unreported catches persist in some areas, including parts of China, sustained by continuing demand for whale shark products (Rowat & Brooks, 2012; Pierce & Norman, 2016). Bycatch remains a harder threat to control. Whale sharks often associate with tuna schools and are accidentally captured in purse-seine and gillnet fisheries; although many regulations require their release, some individuals are retained or die from capture and handling (Rowat & Brooks, 2012; Pierce & Norman, 2016).

Plastic pollution is an emerging concern: because whale sharks filter enormous volumes of seawater, they may inadvertently ingest microplastics and larger debris alongside their natural food, raising concern over long-term health effects, though the population-level impact remains difficult to measure (Germanov et al., 2018). Satellite-tracking data combined with global shipping records show that around 92% of whale sharks' horizontal range and nearly 50% of their vertical range overlap with areas of heavy vessel traffic. Because animals injured or killed by ships often sink rather than reach shore, many vessel-related deaths likely go unrecorded, suggesting the true toll of ship strikes is substantially underestimated (Womersley et al., 2022).

What a Decade of Satellite Tracking Has Revealed

Some of the most significant recent whale shark research has taken place in Indonesia, home to the Bird's Head Seascape and the Coral Triangle critical habitats for the Indo-Pacific population. A collaboration involving the Elasmobranch Institute Indonesia, Konservasi Indonesia, Conservation International, and university researchers from Australia and Indonesia has tracked whale sharks by satellite for more than a decade (Putra et al., 2026). More than 70 whale sharks were tagged, with tags remaining active for an average of over 400 days and, in one case, nearly 990 days producing one of the largest satellite-tracking datasets available for the species. Research published in *Frontiers in Marine Science* in 2026 found that whale sharks in the region cross at least 13 national maritime boundaries, with males spending approximately 40% of their lives outside any national jurisdiction (Putra et al., 2026).

The research also illuminated whale shark aggregation ecology. While aggregations are typically seasonal elsewhere, Cenderawasih Bay and Saleh Bay were found to support year-round feeding aggregations, and newborn whale sharks recorded in Saleh Bay suggest it may serve as an important nursery habitat. These findings are informing conservation planning, including Indonesia's efforts with local communities to establish a marine protected area dedicated to whale sharks, and contributed to a seamount-protection resolution adopted at the March 2026 CMS Conference of the Parties (Putra et al., 2026). A separate study of 115 whale shark stranding records collected in Indonesia over 13 years found that reported strandings rose considerably from 2020 onward, likely reflecting greater public awareness and reporting rather than a proportional rise in actual mortality. Nonetheless, the study identified concerning patterns: juveniles accounted for a large share of

strandings, and stranding timing and location appeared linked to regional oceanographic conditions warranting systematic, ongoing monitoring rather than reactive response alone.

Findings from other regions have been less encouraging. At Praia do Tofo in southern Mozambique, a 15-year photo-identification study of more than 700 individuals (2005–2019) documented a continuing, serious decline in local sightings. Larger juveniles and adults particularly individuals longer than about seven metres showed the steepest decline, falling by roughly 99%, with overall sightings down about 87% and estimated abundance down 89% (Auditore et al., 2025). Researchers found no strong evidence that environmental shifts or redistribution could fully account for this decline, raising concern that it reflects a genuine regional population collapse rather than a change in distribution an important counterpoint to the more encouraging Indonesian findings.

New technology is also deepening behavioural understanding. In 2026, researchers from the Australian Institute of Marine Science reported findings from small cameras mounted on tagged whale sharks' fins, directly observing feeding behaviour previously inferred only indirectly. The study identified 36 distinct feeding behaviours, revealing a far wider foraging strategy than previously assumed including active searching throughout the water column and near the seafloor, not just surface plankton feeding (Barry et al., 2026). Citizen science and artificial intelligence are further transforming monitoring: AI-based systems can match the unique spot patterns in photographs submitted by divers and tourists to identify individual whale sharks, greatly expanding the geographic reach of data collection beyond professional research teams (Arzoumanian et al., 2005).

Turning Knowledge into Protection

Translating scientific knowledge into effective long-term conservation remains difficult. Marine protected areas around key aggregation sites including Ningaloo Reef in Western Australia, the Bird's Head Seascape in Indonesia, and Isla Holbox in Mexico continue to form the backbone of conservation efforts (Rowat & Brooks, 2012; Pierce & Norman, 2016). Ningaloo Marine Park, in particular, is often cited as a model for combining conservation with tourism through rules governing tourist location and behaviour during swim-with-whale-shark activities; a 2025 review in *Frontiers in Conservation Science* highlighted this as a useful approach for reducing disturbance while sustaining tourism (Hammerton et al., 2025).

Yet satellite-tracking studies reveal an important limitation of protected-area-based conservation: whale sharks do not remain within protected boundaries throughout their lives, instead crossing national borders and moving into international waters. Protecting isolated aggregation sites alone therefore cannot fully safeguard the species (Putra et al., 2026). Effective conservation planning must instead connect feeding and nursery habitats with migratory corridors spanning multiple countries and the high seas a far more complex undertaking that depends on international cooperation and still-developing frameworks for governing high-seas areas (Womersley et al., 2022; Putra et al., 2026). Local community involvement has also proven essential. In Indonesia, the same fishers whose bagan nets attract whale sharks have become valuable research partners, providing access to fishing grounds, local knowledge, and sighting information (Himawan et al., 2015); similar partnerships have emerged in tourism-dependent regions. Recent reviews of shark conservation more broadly emphasise the need for interdisciplinary approaches that address not only biology and population status but also interactions

with fisheries, human activities, and management, while highlighting persistent gaps in understanding the combined effects of multiple pressures and the social and economic dimensions of conservation (Queiroz et al., 2019; Dulvy et al., 2021).

The Road Ahead

Research over the past two years has substantially expanded understanding of whale shark conservation, yet the species' future remains uncertain. Satellite tracking has clarified migration routes, likely nursery areas, and the extent of time spent in international waters, while long-term monitoring has shown that populations do not automatically recover once direct fishing pressure eases the steep decline documented in Mozambique demonstrates that halting targeted fishing alone may be insufficient to restore populations (Putra et al., 2026).

New technologies are simultaneously creating better monitoring opportunities: biologging cameras are yielding direct behavioural data, artificial intelligence is enabling analysis of citizen-submitted photographs, and genetic and genomic tools are opening new avenues for population study (Auditore et al., 2025). Policy responses are also advancing, including the proposed strengthening of CITES protections, plans for a new whale shark-focused marine protected area in Indonesia, and CMS actions targeting connected marine habitats (CITES, 2025; CMS, 2026; Putra et al., 2026) signalling that conservation policy is gradually catching up with the scientific evidence.

Three major gaps remain. First, conservation must extend beyond individual aggregation sites to encompass migration routes and international waters. Second, modern threats such as vessel collisions and plastic pollution must be addressed alongside long-standing threats like fishing and illegal trade. Third, sustained

cooperation with local communities, fishermen, and citizen scientists must be maintained, given the importance of these partnerships for collecting data across vast areas.

Conclusion

Whale sharks take decades to reach maturity, and their populations may require even longer to recover from serious declines. The conservation decisions made during the present decade may therefore not show their full effects for many years to come, making this a particularly consequential period. Researchers now possess better data, a clearer understanding of the major threats, and improved conservation technologies than ever before yet the window of opportunity to prevent further population decline remains limited. Bridging the gap between site-based protection and the migratory, transboundary reality of whale shark life history, while sustaining the community partnerships that make long-term monitoring possible, will be essential to securing the future of the world's largest fish.

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Beyond a Physical Barrier: Fish Mucus as an Emerging Source of Bioactives

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ABSTRACT

Fish mucus is often viewed as a physical barrier on the fish body separating it from the aqueous environment. However, it is actually a biologically active layer that plays an important role in protecting fish. It is rich in mucin proteins, antimicrobial peptides, enzymes, immune-related proteins, lipids, and other bioactive compounds. Mucus protects against pathogens and environmental challenges. Recent studies have also highlighted its antimicrobial, wound-healing, anti-inflammatory, and other potentially beneficial properties. In addition, microorganisms naturally associated with fish mucus may contribute to disease resistance and offer possibilities for probiotic applications in aquaculture. These findings are expanding our understanding of fish mucus from a protective barrier to a promising natural source of bioactive compounds. Further exploration of these molecules could open new avenues for their application in cosmetics, biotechnology, aquaculture and biomedicine.

KEYWORDS

Epidermal secretion; Marine Bioactives; Antimicrobial activity; Wound healing; Mucosal defence

Introduction

Fish live in an environment filled with microorganisms, parasites, pollutants, and other potential threats. Yet, before many of these hazards can reach the living tissues beneath the skin, they encounter a thin, slippery layer of mucus. Produced primarily by specialised mucus-secreting cells, fish epidermal mucus is much more than a simple coating on the body. It forms a dynamic interface between the fish and its aquatic surroundings and serves as one of the first lines of defence against biological and environmental challenges (Dash et al., 2018). The mucus layer is continuously produced and shed, helping to trap microorganisms and limit their attachment and colonisation on the skin. At the same time, its complex biochemical composition gives it functions that extend far beyond a physical barrier. Mucins, glycoproteins, antimicrobial peptides, enzymes, lipids, metabolites, and immune-related proteins work together to support pathogen defence and other protective processes (Reverter et al., 2018). Increasing evidence also suggests that some components of fish mucus may contribute to tissue protection and wound healing (Kwan and Ismail, 2018; Yuliana et al., 2025). Thus, this outer epidermal secretion represents a diverse natural reservoir of bioactive molecules with potential value not only for maintaining fish health but also for biomedical and biotechnological applications.

Protective role of fish mucus

Physical barrier

The protective function of fish mucus results from the combined action of its physical properties, bioactive molecules, and associated microbial community. Mucins give the mucus layer its viscous, slippery nature, helping trap microorganisms and interfere with their attachment and colonisation on the skin. The continuous production and shedding of mucus can further help remove trapped organisms and unwanted materials from the epidermal surface. In addition to protecting against abrasion, the mucus layer can act as an interface between the fish and potentially harmful environmental substances, including toxic compounds and

heavy metals (Reverter et al., 2018). The viscoelastic properties of mucus can also help limit the movement of motile microorganisms across the skin surface (Reverter et al., 2018). Importantly, mucus is not a static barrier. Its production and biochemical composition can change in response to environmental and biological conditions such as stress and pathogen exposure. Changes in mucus secretion and composition during pathogen challenge suggest that the mucus layer can actively respond to threats rather than simply forming a permanent covering over the skin (Reverter et al., 2018). This dynamic nature allows the fish to maintain a responsive protective surface while continuously interacting with its aquatic environment.

Antimicrobial properties

One of the most important protective properties of fish mucus is its antimicrobial activity. The mucus contains a diverse group of molecules, including antimicrobial peptides (AMPs), lysozyme, lectins, complement proteins, immunoglobulins, enzymes, and other antimicrobial proteins (Dash et al., 2018; Reverter et al., 2018). AMPs are particularly important components of innate mucosal defence and include molecules such as piscidins, defensins, pardaxin, cathelicidins, and histone-derived peptides (Reverter et al., 2018). These molecules can act rapidly against invading microorganisms. Some AMPs interact with microbial membranes and disrupt their integrity, while others act through different mechanisms. Lysozyme provides another important form of antibacterial defence by breaking bonds within the peptidoglycan structure of bacterial cell walls, thereby weakening the bacterial envelope (Dash et al., 2018). Other immune-related proteins, including C-reactive proteins, also contribute to innate defence at the mucosal surface. Transferrin provides a different protective mechanism by binding iron and reducing its availability to microorganisms, thereby limiting the resources needed for their growth (Dash et al., 2018). Histone-derived molecules found in fish mucus have also been reported to show antibacterial, antifungal, and

antiparasitic activities, illustrating the broad spectrum of chemical defence associated with the mucus layer (Reverter et al., 2018). Together, these different components allow mucus to defend the fish through multiple complementary mechanisms rather than relying on a single antimicrobial compound.

Protection can also involve the microorganisms that naturally inhabit the mucus. The mucus surface supports diverse microbial communities, some of which may contribute to host defence by producing substances that inhibit potential pathogens. For example, Lowrey et al. (2015) reported that bacterial isolates associated with rainbow trout skin mucus inhibited the growth of aquatic fungal pathogens. More recently, Leonora and Caipang (2025) reviewed bacterial isolates from fish mucosal surfaces that showed probiotic characteristics or antagonistic activity against pathogens, suggesting that these resident microorganisms may represent an additional component of mucosal defence and a potential resource for aquaculture applications.

The protective role of mucus also involves broader mucosal immune responses. Immunoglobulins, complement proteins, lectins, and other immune-related molecules present in mucus participate in immune recognition and defence (Dash et al., 2018; Reverter et al., 2018). Some fish mucus AMPs have also been reported to influence B-cell functions, suggesting that these peptides may contribute to mucosal immune responses in addition to their direct antimicrobial activity (Reverter et al., 2018). Evidence from zebrafish further suggests that mucus can have immunomodulatory functions. Adult zebrafish mucus has been reported to influence immune responses induced by dextran sulfate sodium (DSS) in larvae and has been proposed to contribute to maternal immune protection (Wang et al., 2024).

Mucus contains diverse lipid components, including saturated, monounsaturated, and polyunsaturated fatty acids, which may contribute to protection against pathogenic invasion (Dash et al., 2018).

Recent evidence also demonstrates species-specific antimicrobial activity. For example, mucus from *Cilus gilberti* has shown activity against *Vibrio* strains, which are important pathogens in aquaculture, further highlighting the protective potential of fish mucus (Alvarez et al., 2026). Some mucus components have more specialised protective functions.

Wound healing properties

The protective properties of mucus become particularly important when the skin is damaged. A wound disrupts the normal barrier of the skin and exposes underlying tissues to the surrounding environment, creating a need for both protection and tissue repair. The mucus layer can help protect the injured surface while its bioactive components may also support processes involved in wound healing.

Experimental evidence supports the wound-healing potential of fish mucus. Deo et al. (2016) investigated the crude mucus extract of the marine catfish *Osteogobius militaris* using both in vivo and in vitro models. Treatment with mucus extract enhanced wound contraction compared with the control. After seven days of treatment, wounds receiving mucus extract also showed higher hydroxyproline levels, a marker associated with collagen synthesis. In addition, lysyl oxidase activity increased with increasing mucus concentration, suggesting an association with processes involved in collagen maturation and tissue repair. The mucus extract also showed angiogenic activity in the chick chorioallantoic membrane model, with marked neovascularisation observed at the highest dose tested. Together, these findings provide experimental evidence that fish mucus contains components capable of supporting several processes associated with wound healing, including wound contraction, collagen-related tissue repair, and angiogenic activity (Deo et al., 2016).

More recently, Yuliana et al. (2025) reported that mucus from snakehead fish (*Channa striata*) accelerated wound healing and exhibited antibacterial activity against *Staphylococcus aureus*. The 15% mucus

formulation produced the strongest effects and showed wound-healing activity comparable to the positive control. The combination of antibacterial and wound-healing effects is particularly noteworthy because successful repair of an injured surface requires both protection from microbial invasion and restoration of damaged tissue. These findings suggest that fish mucus may contain a combination of bioactive components that contribute to both defence and repair, although the specific molecules responsible for these effects and their mechanisms of action remain to be established.

Anti-inflammatory and Antiarthritic Properties

Recent studies suggest that fish mucus contains bioactive compounds capable of regulating inflammatory responses. By reducing excessive inflammation, these compounds may help protect tissues from further damage and support the healing process. The anti-inflammatory activity of fish mucus has generated interest in its possible application for managing inflammatory disorders, including arthritis. Although research in this area is still limited, preliminary findings indicate that mucus-derived compounds could serve as potential candidates for the development of natural anti-inflammatory products.

Antihypertensive Properties

Fish mucus has also attracted attention as a source of bioactive peptides with antihypertensive activity. Some peptides isolated from aquatic organisms have been shown to inhibit angiotensin-converting enzyme (ACE), an enzyme involved in blood pressure regulation. By interfering with ACE activity, these compounds may help maintain normal blood pressure levels. Although research on fish mucus-derived antihypertensive compounds remains at an early stage, the available evidence suggests promising possibilities for future therapeutic applications.

Haemolytic Properties

Certain components of fish mucus exhibit haemolytic activity, meaning they can disrupt red blood cell membranes. These

compounds are believed to play a defensive role by protecting fish against predators, parasites, and invading microorganisms. Although haemolytic activity may contribute to the natural defence mechanisms of fish, it also highlights the need for careful evaluation of mucus-derived compounds before they are developed for biomedical applications. Understanding both the beneficial and potentially harmful effects of these compounds is essential for their safe utilisation.

Other protective roles

Protective functions of mucus also involve other bioactive components beyond antimicrobial peptides and immune-related proteins. Reef fish mucus, for instance, contains mycosporine-like amino acids (MAAs), which can protect against solar radiation (Braun et al., 2016). Together, these findings demonstrate that the protective properties of fish mucus arise from a diverse mixture of bioactive molecules with different functions, ranging from direct antimicrobial activity to protection from environmental stressors.

Potential Applications of Fish Mucus-Derived Bioactives

The diverse biological properties of fish mucus have attracted considerable interest in aquaculture, biotechnology, and medicine. The antimicrobial compounds present in mucus may provide environmentally friendly alternatives for disease control in aquaculture. Similarly, mucus-derived bioactive molecules with wound-healing, anti-inflammatory, and antihypertensive properties could contribute to the development of novel therapeutic products.

Advances in proteomics and biochemical analysis have revealed numerous proteins and peptides in fish mucus associated with immune defence and tissue repair. However, further research is required to identify the active compounds, understand their mechanisms of action, assess their safety, and evaluate their commercial potential.

Prospective species for mucus collection

A few fishes, such as murels, catfishes, eels, toadfishes, pufferfish, etc produce a high amount of mucus. Fish mucus is generally

collected by gently scraping the body surface using sterile equipment under controlled conditions.



Fig. Collection of Mucus from fish

Conclusion

Fish epidermal mucus is far more than a physical coating on the skin. Its complex mixture of mucins, antimicrobial peptides, enzymes, immune-related proteins, lipids, and other bioactive molecules protects against pathogens and environmental challenges. The microorganisms associated with the mucus may further contribute to this defence and represent a potential source of beneficial probiotics for aquaculture. Emerging experimental evidence also points to wound-healing potential, although many of the molecules involved remain to be identified and their specific functions require validation. Together, these findings highlight fish mucus as a promising natural reservoir of protective and healing bioactives with potential value in aquaculture and biomedicine.

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Fishing Gear That Leaves Less Behind: Innovations for Safer, More Sustainable Seas

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ABSTRACT

Abandoned, lost or otherwise discarded fishing gear (ALDFG), commonly known as “ghost gear,” is a persistent source of marine pollution and a significant threat to marine organisms and habitats. Although fishing gear is designed for efficient and durable operation, its loss or abandonment can allow nets, lines, pots and ropes to continue catching or entangling marine animals long after they have left the control of fishers. This article highlights emerging solutions to reduce this impact, including biodegradable fishing gear, gear marking, tracking and navigation technology and recycling of discarded nets. Wider adoption of these innovations can support sustainable fisheries by reducing marine pollution, protecting biodiversity and minimizing resource loss. Designing fishing gear for durability, recovery, recycling and reduced environmental impact can promote a more circular and resilient fisheries sector, while safeguarding healthy oceans, sustainable livelihoods and long-term food security.

KEYWORDS

Biodegradable fishing gear; bycatch reduction; circular economy; ghost gear; marine plastic pollution

Introduction

Fishing gear is designed to catch aquatic organisms efficiently, but when it is abandoned, lost or discarded (ALDFG), it can continue to catch and kill marine life long after it has left the hands of fishers. This phenomenon, known as “ghost fishing,” makes lost fishing gear a persistent threat to marine biodiversity, habitats and ocean health. ALDFG also contributes substantially to marine litter and can fragment into microplastics, creating impacts that extend well beyond the initial loss of the gear. The scale and persistence of the problem highlight the need for a fundamental shift in how fishing gear is designed and managed. Gear loss can result from adverse weather, seabed entanglement, interactions with other fishing operations, operational pressures and economic constraints. Bottom-contact and unattended gear, including trawls, traps, pots and gillnets, are particularly vulnerable to loss. Once lost, synthetic fishing materials can remain in the marine environment for decades or even centuries, while continuing to interact with marine organisms. These challenges are driving a new generation of innovation focused not only on preventing gear loss, but also on reducing the consequences when loss occurs. The emerging approach considers fishing gear across its entire life cycle—from design and material selection to deployment, retrieval, recovery and end-of-life management. The innovation agenda is therefore built around three complementary priorities: better prevention, safer materials and more effective recovery (Pandey et al., 2025).

Innovations That Prevent Loss

Preventing the loss of fishing gear represents the most cost-effective strategy for mitigating ALDFGs impacts. Preventative measures are generally more economically efficient than remedial interventions, while also contributing to broader fisheries management objectives, including improved operational efficiency, resource conservation, and long-term sustainability.

Gear Marking: International agreements increasingly encourage the marking of fishing gear to help identify its owners and promote the reporting of lost gear. Traditional methods, such as flags, reflectors, buoys, inscriptions, and tags, are now being complemented by electronic buoys and other electronic marking technologies being tested in different fisheries. In addition to helping identify and recover lost gear, proper marking makes passive fishing gear more visible to passing vessels, reducing navigational risks and the likelihood of accidental damage or gear loss (He and Suuronen 2018).

Tracking and navigation technology: GPS and seafloor mapping reduce the chance of losing gear through accidental contact with the seabed. Radar reflectors and radio buoys on fishing gear reduce the risk of loss, avoid interactions with towed gear, and make lost gear easier to locate, while markers of gear position below the surface reduce the risk of damage from being cut by passing vessels (Macfadyen et al. 2009).

Design, inputs, and rules of the fishery: Reducing gear loss requires improved gear design, appropriate material selection, and responsible fishing practices. Limiting fishing effort and soak time, regular gear monitoring and retrieval, and spatial-temporal separation of fishing operations can minimize gear loss and ghost fishing. Effective surveillance, enforcement, and deterrents against IUU fishing are also essential to prevent intentional gear abandonment and at-sea discarding (Pandey et al., 2025).

Innovations That Make Lost Gear Less Deadly

As gear loss cannot always be completely avoided, next-generation fishing gear is being developed to minimize its environmental impacts through biodegradable materials, escape mechanisms, and rapid deactivation or neutralization after loss.

Biodegradable and less durable gear: The persistence of conventional plastic fishing gear contributes to long-term aquatic pollution and increases the risks of entanglement, ingestion,

and ghost fishing. To address these impacts, biodegradable alternatives are being explored for nets, fishing lines, pots, lures, and soft lures. A key approach is to modify the material composition of fishing gear so that it maintains adequate mechanical strength and fishing efficiency during normal operation but degrades more rapidly after loss (Byrnes and Dunn, 2020).

Recent research has investigated biodegradable polymers such as polybutylene succinate (PBS) and polybutylene adipate terephthalate (PBAT) as potential alternatives to conventional nylon in fishing nets, pots, and lines. As the material degrades, the loss of structural integrity can reduce the fishing efficiency of derelict gear and facilitate the escape of trapped organisms. Similarly, degradable escape panels and release components in traps can provide an effective means of rapidly reducing ghost-fishing activity. Biodegradable lures and soft lures can further reduce the persistence of fishing-related plastic debris in aquatic environments (Deroine et al., 2019; Byrnes and Dunn, 2020; Pandey et al., 2025). The major challenge is to achieve an appropriate balance between operational strength, fishing performance, durability, and controlled degradation after gear loss. Despite these challenges, biodegradable materials and gear designs offer a promising pathway towards reducing the environmental persistence and ecological impacts of lost fishing gear.

Bringing Gear Back: Retrieval, Reporting, and Circularity

Recovery of lost fishing gear is an important component of ALDFG management, as timely retrieval can prevent continued ghost fishing, habitat damage, and navigational hazards. Accurate reporting of gear loss is therefore essential for identifying high-risk areas, understanding the causes and scale of gear loss, and enabling targeted recovery. A non-punitive reporting system can encourage fishers to report losses without fear of penalties, thereby improving opportunities for retrieval. The effectiveness of recovery also

depends on gear type and timing; for example, gillnets may require rapid retrieval because their fishing efficiency can persist after loss, whereas lost traps and pots may remain recoverable over longer periods. Effective retrieval should be supported by accessible port reception facilities, dedicated recovery programmes, and appropriate economic incentives for fishers to return lost, damaged, or end-of-life gear. Recovered gear can subsequently be directed towards reuse, recycling, or other material-recovery pathways, supporting a more circular fishing-gear economy. Training and awareness programmes can further improve fishers' capacity to prevent gear loss and safely recover ALDFG. At the international level, initiatives such as the Global Ghost Gear Initiative (GGGI) promote best-practice approaches for preventing, retrieving, and managing lost fishing gear across the seafood supply chain (Pandey et al., 2025).

Governance: The Framework That Lets Innovation Work

Innovation can achieve its full potential only when supported by an effective governance framework. An international policy architecture for addressing abandoned, lost and discarded fishing gear (ALDFG) already exists in part. The International Maritime Organization (IMO), through MARPOL, provides the principal international framework for preventing pollution from ships, while the United Nations Environment Programme (UNEP) addresses ALDFG within the broader context of marine litter. The Food and Agriculture Organization of the United Nations (FAO) promotes responsible fishing practices through its Code of Conduct for Responsible Fisheries, complemented by the Voluntary Guidelines for the Marking of Fishing Gear. These guidelines distinguish abandoned gear as fishing gear unintentionally left at sea under unforeseen circumstances, lost gear as gear that inadvertently goes out of the owner's control, and discarded gear as gear released without an attempt at recovery.

Despite these existing instruments, ALDFG remains a persistent challenge, indicating that policy frameworks alone are not sufficient. Effective management must account for the diversity of fishing gears, operating environments, target species and socio-economic conditions across fisheries. Consequently, a uniform approach is unlikely to be effective. Instead, successful interventions require fishery-specific strategies developed through collaboration among fishers, fishing industries, resource managers, researchers and other relevant stakeholders. Such participatory approaches can improve both the practicality of interventions and their acceptance at the community level (Pandey et al., 2025).

Conclusion

Addressing abandoned, lost and discarded fishing gear requires a shift from simply managing lost gear to preventing its loss and reducing its impacts throughout its life cycle. No single innovation can solve the problem; effective solutions must combine improved gear design, marking and tracking, responsible fishing practices, timely retrieval, safer materials, and recycling. The success of these approaches depends on practical, affordable solutions developed with fishers and supported by effective reporting systems, recovery incentives, port facilities and sound governance. Ultimately, sustainable fishing gear is not only gear that performs efficiently at sea, but gear that is designed to be recovered, reused or recycled—and to leave less behind when its working life ends. Bringing science, innovation, policy and fishing communities together can help build healthier oceans and more resilient, sustainable fisheries.

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Microbes with a Mission: How CRISPR Is Cleaning Our Waters

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ABSTRACT

The CRISPR-Cas9 gene-editing technology became a revolutionary gene-editing technology in microbial biotechnology with new measures of sustainable wastewater treatment and pollution control. CRISPR can be used to develop engineered microbes through refined and effective genetic changes to increase; pollutant breakage, heavy-metal detoxification, and overcoming antibiotic resistance in aquatic systems. Outside of genome editing, CRISPR-based biosensors including Cas12 and Cas13 enable rapid pathogen and antimicrobial resistance gene detection in wastewater, and have a fast and sensitive diagnostic efficiency. Combination of CRISPR with metabolic engineering, artificial intelligence (AI), and high-throughput screening leads to its increased potential, the way to intelligent, adaptive, and sustainable wastewater management. Although deliveries are still facing some challenges like off-target effects, delivery inefficiencies, and ethical issues, improved CRISPR 3.0 technologies with base and primer editing can be seen as a new dawn in efficient and environmentally friendly wastewater management in future environmental protection.

KEYWORDS

CRISPR-Cas9; Microbial genome editing; Wastewater bioremediation; Antimicrobial resistance

Introduction

Over the decades, microorganisms have been critical in the process of eliminating pollutants that threaten ecosystems and human health like pesticides, heavy metals and persistent organic pollutants (POPs). These microbes aid in the restoration of the environment balance through their processes of natural detoxification and decompositions. Nevertheless, Modern pollutants (especially heavy metals) are increasingly complex and persistent and thus may exceed the ability of natural microbial systems to cope. The conventional form of bioremediation methods, whereby naturally occurring microorganisms are used to degrade harmful of substances, are slow, ineffective, and very much environmental dependent. Although recent developments in the field of molecular biology and metagenomics have helped to improve our knowledge of microbial diversity and functional roles, the new technologies have failed to keep up with the growth rate and complexity of environmental contamination. The groundbreaking technology of gene-editing known as CRISPR-Cas9 has changed microbial engineering. CRISPR enables researchers to control the specifics of genomic editing of microbes, improving or remaking bacteria that can degrade pollution in a more effective way. Using these targeted genetic modifications, engineered microbes are now capable of being customized to clean up heavy metals, degrade organic contaminants, and act in synergy in microbial consortia to address a number of contaminants at the same time. Combining environmental science and innovative biotechnology offers an extremely strong and effective solution to wastewater treatment and overall pollution reduction in the world.

CRISPR-Cas9

CRISPR-Cas9 is one of the most disruptive innovations of modern biotechnology that transformed the process of genetic modification in a vast variety of organisms. First found in bacteria

and archaea as a component of their adaptive immune system, allows microorganisms to have memories of viral infections through segments of viral DNA stored in their own genome. These stored sequences are referred to as CRISPRs, which conduct the Cas9 enzyme to cut and inactivate the genetic code of the invader with accuracy in case they recur.

In essence, CRISPR-Cas9 uses a guide RNA to guide the protein of Cas9 that is applied as molecular scissors to cut DNA at a specific point. Also, new variants of Cas9 can switch genes on and off without any incisions into the DNA, opening new prospects of controlling biological processes.

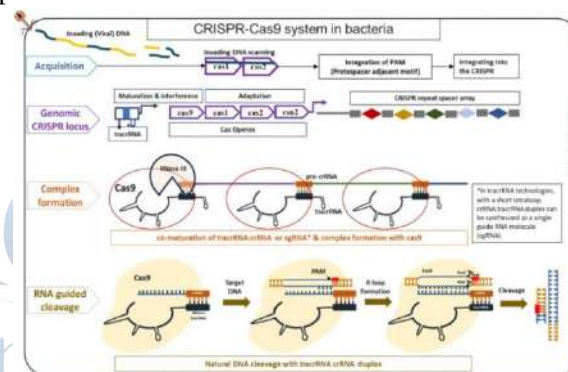


Fig: CRISPR-Cas System in bacteria (Bhanu et al., 2024)

Adaptation of CRISPR-Cas9 for Microbial Genome Editing

The use of CRISPR-Cas9 technology in the editing of the microbial genome has generated important developments in environmental biotechnology. In order to make the most of CRISPR in microbes, a number of important elements of the system have been optimized:

- 1) **Vector Design:** CRISPR-Cas9 elements are generally transferred into microbial cells through the plasmids. These plasmids will be designed to express either the Cas9 protein or the single guide RNA (sgRNA), or it can be integrated in the microbial genome to be expressed over time.
- 2) **Target Gene Selection:** With the aid of bioinformatics programs, including CHOP-IT and

CRISPRdirect scientists can make highly specific sgRNA so that only the target gene sequence is altered.

3) Delivery Mechanisms: CRISPR-Cas9 factors are incorporated into cells of microorganisms by electroporation, conjugation, or transformation. In more complex applications, to deliver whole libraries of guide RNAs, such systems as piggyBac transposons are applied to facilitate massive genetic modifications.

Advanced Gene Editing Techniques

With the ongoing development of the CRISPR-Cas9 technology, researchers have devised new gene-editing methods to increase the accuracy and flexibility of microbial engineering. Recombineering is one such strategy that combines recombinational engineering with CRISPR-Cas9 to make editing much more efficient. Under this method, microbial genomes are exposed to short DNA fragments so as to have accurate genetic modifications. An example is the Single-Strand DNA Recombineering (SSDR) system that uses single-stranded DNA fragments to fine-tune individual genes, and Double-Strand DNA Recombineering (DSDR) that uses two-stranded DNA to afford superior and reliable genome editing- especially in bacterial organisms such as *Escherichia coli*.

Non-Homologous End Joining (NHEJ) is another breakthrough which is a DNA repair mechanism that cements pieces of broken DNA strands, without requiring a homologous template. NHEJ is not as specific as homologous recombination, but comes in handy especially to produce targeted gene knockouts in microbes that inherently lack an efficient DNA repair mechanism.

Application prospects in wastewater bioremediation

The combination of CRISPR technology with metabolic engineering has given rise to engineered microbes with the ability to survive in severe environmental conditions and also to degrade toxic substances effectively. CRISPR-Cas9 has massive potential in the next-generation

wastewater treatment due to its accuracy, low cost, and high performance. CRISPR technology will turn microbes into effective environmental partners with an augmented detoxification and resistance capability, which can help achieve a more sustainable and less polluted environment.

In addition to gene editing, CRISPR-Cas is redefining the detection of pathogens using their marvelous speed, accuracy, and ease. Due to their enhanced ability to identify and cleave certain genetic sequences, including CRISPR-Cas12 and Cas13 have become potent biosensing platforms with great potential of conducting real-time molecular diagnostics. CRISPR-based assays have been effectively established to detect viral RNA, such as SARS-CoV-2, in wastewater and also pathogenic bacteria such as *Salmonella*, *E.coli*, *Listeria monocytogenes*, and *Mycobacterium tuberculosis*.

Application prospects in pathogen detection

It is possible to combine CRISPR technology with nucleic acid amplification methods to enable scientists to detect pathogens with high sensitivity at the point of care. It is a combination of these that makes an accurate and fast detection of infectious agents that gives early signs of disease outbreaks. In addition, it is an effective instrument in managing and evaluating the efficiency of wastewater treatment systems with a colossal potential to the community health and environmental security.

Application prospects in ARG/AMR control

Antibiotics have extensively been used and thus, this has resulted in the prevalence of antibiotic-resistant bacteria and antibiotic resistance genes (ARGs) in water bodies and is a major threat to global health. CRISPR-Cas system is an effective innovative approach in the detection and combating antimicrobial resistance (AMR). High sensitivity biosensors based on advanced solutions such as Cas12 and Cas13 have been created to amplify detection of AMR genes in wastewater, with CRISPR-Cas9 able to be

programmed to cut and silence multi-drug resistance plasmids. Innovative methods like the incorporation of CRISPR into portable diagnostics or the use of the system together with the isothermal amplification technique make it possible to conduct quick on-site testing of water samples. Also, it is also possible that researchers will use engineered bacteriophages to introduce CRISPR components to wastewater systems, which selectively target and cause the elimination of resistant bacteria.

Challenges, Limitations, and Ethical Considerations

Although the CRISPR-Cas technology has great potential, there are several limitations to its application, which need to be resolved to use it safely and effectively. The first is the potential of off-target effects, i.e. Cas enzymes accidentally cleaving non-target DNA sequences, which leads to random mutations. The genetic diversity, repetitive DNA areas and the lack of efficient delivery contribute to additional complications of microbial genome editing and decreases the accuracy and safety. Resistance of microorganisms to CRISPR based treatment may also develop with time.

A host immune response to Cas9 proteins is another challenge as most organisms such as human beings have immunity that precedes the exposure to Cas9 proteins thus reducing the efficiency of editing. In addition, the size of Cas9 is very large, not to mention the dangers of immune elimination and protein degradation, thus it is difficult to deliver CRISPR fragments to target cells safely and effectively. Besides, the possibility of introducing genetically modified microbes into the environment and due to the possible misuse, there are important ethical and biosafety issues. To address these challenges, novel methods of delivery systems like nanoparticles or modified vectors and the method of mitigating immune reactions and off-target

toxicity must be developed to make CRISPR usage in environmental biotechnology less risky and less target specific.

Future Directions

The future of CRISPR technology in microbial engineering is in the use of CRISPR technology with automation, artificial intelligence (AI), and high-throughput screening (HTS). Robotic automation and HTS are able to screen engineered microbial strains in a rapid manner, saving a lot of time and money in industrial applications. Meanwhile, machine learning can improve the accuracy of genome editing to reduce off-target effects and forecast complicated metabolic pathways.

The introduction of CRISPR 3.0 technology, such as base and prime editors, CRISPRa/i systems, and CRISPRa/i systems have reached the stage of precision, reversibility, and multiplexed genome-wide alterations with no generation of double-strand DNA breaks. These advances enhance the creation of microbial cell factories with enhanced production capability, ability to endure stresses and biosynthetic functions. In the future, the development of next-generation intelligent fermentation will rely on synthetic microbial consortia, CRISPR-based biosensors and AI-controlled bioreactors.

Conclusions

The accuracy, flexibility, and effectiveness of CRISPR-Cas9 have revolutionized the entire field of microbial genome engineering by making it easy to create engineered microbes that can generate industrial enzymes, pharmaceuticals, and biofuels. Although the combination of AI and machine learning enhances the accuracy of guide RNA (gRNA) design and reduces off-target effects. The base and primer editing tools and the CRISPRa/i systems are emerging and expanding in their use. Despite the challenges in the use of CRISPR technology such as off-target effects and

ethical issues, the rapid development of this technology has continued to push it towards broader, safer, and more sustainable applications in biotechnology, agriculture, and healthcare.

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Recirculating Aquaculture Systems (RAS): Principles, Components and Applications in Sustainable Fish Farming

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ABSTRACT

Recirculating Aquaculture Systems (RAS) are an advanced method of fish and shellfish farming in which water is continuously collected, filtered, treated, and reused within a closed or semi-closed production system. In comparison with conventional pond-based and flow-through aquaculture systems, RAS allows fish to be cultured at high stocking densities while requiring very little water exchange, often less than 10% of the total system volume per day. This helps to reduce overall water consumption and minimize the release of aquaculture effluents into the environment. This article reviews the major components of RAS, including mechanical and biological filtration, aeration and oxygenation, disinfection, and waste management, along with their basic operating principles. The major benefits of RAS, such as efficient use of land and water, improved biosecurity, and reduced dependence on geographical and climatic conditions, are also discussed. However, the technology has certain limitations, including high initial investment, considerable energy requirements, technical complexity, and the possibility of rapid and serious losses in case of system failure. Overall, despite these economic and operational challenges, RAS has considerable potential as a sustainable aquaculture technology for increasing production and meeting the growing global demand for fish and other aquatic food resources.

KEYWORDS

Recirculating Aquaculture System, RAS, bio filtration, sustainable aquaculture, water quality management

Introduction

The global demand for fish and other aquatic food products is continuously increasing due to population growth and rising fish consumption per person. Aquaculture has become an important source of aquatic food and now contributes more than half of the fish available for human consumption globally (FAO, 2022). However, conventional aquaculture practices, including open pond culture and net-pen systems, are associated with several environmental and management problems. These include high water requirements, nutrient-rich effluent discharge, disturbance of surrounding ecosystems, disease transmission, and sensitivity to changes in environmental conditions (Ahmed & Thompson, 2019).

Recirculating Aquaculture Systems (RAS) have been developed as an alternative approach to address many of these limitations. RAS are controlled aquaculture systems in which culture water is continuously treated and reused through a combination of mechanical filtration, biological filtration, aeration, oxygenation, and other water-treatment processes. This technology allows fish to be cultured at relatively high stocking densities while reducing water consumption and environmental discharge (Timmons & Ebeling, 2013). Since RAS facilities can be established indoors and do not necessarily depend on nearby natural water bodies, production can be located close to major markets and population centres. This may reduce the distance required for transporting live fish and fresh products and can improve the efficiency of the production and supply chain (Martins et al., 2010).

Principles of RAS

The basic principle of a Recirculating Aquaculture System (RAS) is the continuous treatment and reuse of water to maintain suitable conditions for the growth and survival of cultured aquatic organisms. During feeding and metabolism, fish consume dissolved oxygen and release metabolic wastes, particularly ammonia, along with solid faecal matter. In an RAS, water from the culture tank is continuously circulated

through different treatment units, where solid wastes are removed, toxic nitrogen compounds are converted, carbon dioxide is reduced, and oxygen is replenished before the treated water is returned to the culture tank (Losordo et al., 1998; Timmons & Ebeling, 2013). Through this continuous circulation and treatment process, RAS can achieve very high water reuse, considerably reducing the requirement for fresh water compared with conventional flow-through systems (Martins et al., 2010).

The major water quality parameters that need to be carefully monitored and controlled in RAS include:

- Dissolved oxygen (DO): Maintained at suitable levels through aeration systems or the addition of pure oxygen to support fish respiration and biological filtration.
- Ammonia and nitrite: These toxic nitrogen compounds are controlled mainly through biological filtration, where beneficial nitrifying bacteria convert ammonia into nitrite and subsequently into the less toxic nitrate.
- Carbon dioxide (CO₂): Produced through fish respiration and microbial activity and removed using degassing or aeration units to prevent harmful accumulation.
- Total suspended solids (TSS): Fish faeces, uneaten feed, and other particulate materials are removed using mechanical filtration units such as drum filters, screen filters, or sedimentation systems.
- pH and alkalinity: Maintained within appropriate ranges because stable pH and sufficient alkalinity are essential for fish health and for the effective functioning of nitrifying bacteria.
- Temperature: Carefully controlled according to the cultured species because temperature directly influences metabolism, feeding activity, growth, oxygen demand, and overall production performance (Timmons & Ebeling, 2013).

Key Components of a RAS

A Recirculating Aquaculture System (RAS) consists of several interconnected units that work together to maintain suitable water quality and provide a healthy environment for cultured organisms. Each component performs a specific function, such as removing solid and dissolved wastes, maintaining oxygen levels, controlling gases, and reducing the risk of disease.

Culture Tanks: Culture tanks are the primary units where fish or other aquatic organisms are reared. They are commonly designed in circular or octagonal shapes to promote effective and uniform water circulation. The circular movement of water helps concentrate faecal matter and uneaten feed toward the central drain, making the removal of solid waste easier and improving the self-cleaning ability of the tank (Timmons & Ebeling, 2013).

Mechanical Filtration: Mechanical filtration is used to remove larger suspended particles, such as uneaten feed, faeces, and other solid materials, from the circulating water. Early removal of these wastes is important because their decomposition can increase the organic load and negatively affect water quality. Drum filters, screen filters, and settling units are commonly used for this purpose. Continuous or regular operation of mechanical filtration helps prevent excessive accumulation of solids within the system (Timmons & Ebeling, 2013).

Biological Filtration (Bio filter): The biological filter is one of the most important components of an RAS because it controls toxic nitrogenous compounds produced from fish metabolism and waste decomposition. Beneficial nitrifying microorganisms convert ammonia first into nitrite and then into nitrate through the nitrification process. Different types of biofilters are used in RAS, including moving bed biofilm reactors (MBBR), trickling filters, and fluidized-bed filters. Effective biofiltration is essential for maintaining safe ammonia and nitrite concentrations in the culture water (Ebeling & Timmons, 2012).

Aeration and Oxygenation: High stocking densities in RAS can result in considerable

oxygen consumption by fish and microorganisms. Therefore, maintaining an adequate dissolved oxygen concentration is essential for fish health, growth, and proper functioning of the biofilter. Aeration devices, diffusers, oxygen cones, and pure oxygen injection systems may be used to supply additional oxygen when normal aeration is insufficient (Timmons & Ebeling, 2013).

Degassing Units: Carbon dioxide (CO₂) is continuously produced through the respiration of fish and microorganisms and can accumulate in a recirculating system. Excessive CO₂ concentrations can negatively affect fish respiration and overall performance. Degassing units are therefore used to remove excess CO₂ from the water. Packed-column degassers, cascade aerators, and other gas-exchange systems are commonly used for this purpose (Timmons & Ebeling, 2013).

Disinfection: Disinfection systems help reduce harmful microorganisms and improve biosecurity within RAS facilities. Ultraviolet (UV) irradiation and ozone treatment are commonly used to reduce pathogen and microbial loads in the circulating water. When properly designed and operated, these systems can improve water quality and reduce disease risks without leaving the same type of persistent chemical residues associated with some conventional disinfectants (Summerfelt, 2003).

Sludge and Waste Management: Solid wastes collected by mechanical filtration systems need to be regularly removed and properly managed. The collected sludge can be dewatered and either disposed of safely or further processed for beneficial uses, such as soil amendment or agricultural fertilizer, depending on its composition and local regulations. Proper waste management reduces environmental impacts and can contribute to circular approaches in aquaculture by recovering useful nutrients from aquaculture wastes (Martins et al., 2010).

Advantages of RAS

Recirculating Aquaculture Systems (RAS) offer several important advantages over conventional aquaculture systems. These

benefits are mainly related to efficient water use, better environmental control, biosecurity, and higher production efficiency.

Water Conservation: One of the major advantages of RAS is the efficient use of water. Since water is continuously treated and recirculated, only a small quantity of new water is generally required to replace losses and maintain water quality. Depending on system design and management, RAS can reuse a very high proportion of the available water, making the technology particularly useful in areas where freshwater resources are limited (Badiola et al., 2012).

Improved Biosecurity: RAS provides a more controlled production environment than open aquaculture systems. Because the culture water is treated and the system has limited contact with external water sources, the introduction and spread of pathogens, parasites, and other unwanted organisms can be reduced. This makes RAS suitable for controlled production and health management, particularly for valuable fish species (Martins et al., 2010).

Better Environmental Control: Important environmental conditions such as temperature, dissolved oxygen, pH, water chemistry, and photoperiod can be monitored and adjusted according to the requirements of the cultured species. As a result, fish can be maintained under relatively stable conditions throughout the year, with less dependence on seasonal and external environmental changes. This can support consistent growth and production performance (Timmons & Ebeling, 2013).

Efficient Use of Land: RAS allows fish to be cultured at relatively high stocking densities, resulting in greater production from a comparatively small land area. This makes RAS especially useful where suitable land for conventional ponds is limited or expensive. Vertical and indoor production approaches can further improve the efficiency of land use (Badiola et al., 2012).

Flexible Location of Production: Unlike many conventional aquaculture systems, RAS facilities do not necessarily need to be located near large natural water bodies. They can be

established close to cities, markets, or processing facilities. Producing fish closer to consumers can reduce transportation requirements, shorten distribution time, and potentially improve product freshness (Martins et al., 2010).

Better Effluent Management: In RAS, waste products are concentrated and removed from the circulating water rather than being continuously released into the surrounding environment. Solid waste and nutrient-rich water can therefore be collected, treated, and, where appropriate, reused or further processed. This provides opportunities for better nutrient recovery and contributes to more sustainable and circular aquaculture practices (Martins et al., 2010).

Challenges and Limitations

Although RAS provides several environmental and production benefits, its operation also involves significant technical and economic challenges.

High Initial Investment: The establishment of an RAS facility requires considerable initial investment. Costs are associated with culture tanks, pumps, mechanical and biological filtration units, oxygenation equipment, monitoring instruments, buildings, and control systems. Therefore, the initial investment can be substantially higher than that required for some conventional aquaculture systems (Badiola et al., 2012).

High Energy Requirement: RAS depends on continuous operation of pumps, aeration and oxygenation systems, filtration equipment, temperature-control units, and other electrical components. Consequently, energy consumption can represent a major part of operating costs. High energy demand may also increase the environmental footprint of RAS when electricity is generated from fossil fuels (Martins et al., 2010).

Technical and Operational Complexity: RAS is a highly integrated system in which the failure or poor performance of one component can affect the entire production process. Skilled personnel are required to monitor water quality, maintain biofilter performance, operate

mechanical equipment, and respond quickly to changes in dissolved oxygen, ammonia, pH, temperature, and other parameters (Timmons & Ebeling, 2013).

Risk of Rapid System Failure: Because fish are generally maintained at high stocking densities, any major failure of pumps, aeration, oxygenation, or electrical systems can rapidly deteriorate water quality. In particular, a prolonged power failure can cause oxygen depletion and may result in severe fish mortality within a short period. Therefore, backup power, emergency oxygen supply, alarms, and continuous monitoring are important components of RAS management (Martins et al., 2010).

Off-Flavor Problems: Off-flavor is another potential problem in RAS production. Compounds such as geosmin and 2-methylisoborneol (MIB) may be produced by microorganisms within the system and can accumulate in fish tissues, resulting in undesirable taste or odor. Depending on the severity of the problem, fish may require a depuration period in clean water before harvest to reduce these compounds and improve product quality (Timmons & Ebeling, 2013).

Applications and Species Suitability

RAS technology has been applied to the production of a wide range of freshwater and marine species. Common examples include Atlantic salmon (*Salmo salar*), tilapia (*Oreochromis spp.*), African catfish (*Clarias gariepinus*), barramundi (*Lates calcarifer*), and several ornamental fish species. The technology is used for different production stages, including hatchery operations, nursery rearing, broodstock management, juvenile production, and grow-out culture (Dalsgaard et al., 2013).

RAS has received particular attention in Atlantic salmon production, especially for land-based farming. The controlled conditions provided by RAS can reduce dependence on marine net-pen environments and help address concerns associated with sea lice, disease transmission, escapes, and nutrient discharge. RAS can also provide greater control over water

quality and production conditions, making it an attractive technology for intensive fish farming (Dalsgaard et al., 2013).

The suitability of a species for RAS depends on several factors, including its tolerance to high stocking density, oxygen requirements, growth rate, temperature preference, feeding behaviour, market value, and ability to adapt to controlled culture conditions. Therefore, RAS is not equally suitable for every species, and system design should be matched to the biological and production requirements of the target species (Timmons & Ebeling, 2013).

Conclusion

Recirculating Aquaculture Systems (RAS) are an important technological development in modern and sustainable aquaculture. These systems support intensive fish production while reducing water consumption, improving biosecurity, and providing better control over environmental conditions compared with conventional aquaculture methods. However, the high initial investment, considerable energy requirements, and need for skilled management continue to limit their wider adoption. Recent developments in efficient filtration systems, automation, monitoring technologies, and the use of renewable energy are helping to overcome some of these limitations and improve the overall feasibility of RAS. With the increasing demand for seafood and growing pressure on land and water resources, RAS has strong potential to become an important part of future sustainable aquaculture, particularly in areas where water and suitable land are limited.

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Printing the Ocean's Bounty: How 3D Printing Is Reshaping Seafood

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ABSTRACT

Global seafood demand is rising even as fish stocks face growing pressure and a substantial share of every catch is discarded as skin, bones, shells, or trimmings. Three-dimensional (3D) food printing, once a novelty reserved for chocolate and pasta, is emerging as a practical answer to both problems at once. By turning surimi, fish gelatin, and other seafood pastes into printable "inks," researchers can build custom-shaped fillets, snacks, and soft foods for people with chewing or swallowing difficulties, all while diverting processing by-products that would otherwise become waste. Some laboratories are pushing further still, bioprinting cultured fish and shellfish tissue from living cells and offering a potential route to seafood produced without any fishing or farming at all. This article surveys how seafood 3D printing actually works, why fish pastes make unusually good printing materials, how food-industry waste is being valorized into desirable new products, and the technical, sensory, and regulatory hurdles that still stand between promising laboratory demonstrations and a genuine place on the supermarket shelf.

KEYWORDS

3D food printing, seafood, surimi, food waste valorization, bioprinting, printability, personalized nutrition

Introduction

Walk through any fish market, and you will see the paradox of modern seafood at a glance: gleaming fillets on ice, and beside them, heaps of heads, skins, shells, and trimmings whose final destination is the dustbin. The world eats more fish and shellfish than ever before, yet a striking share of every catch or harvest never reaches a plate in recognizable form. At the same time, an aging global population is creating millions of people who struggle to chew or swallow conventional food, and health-conscious consumers are asking for meals tailored to their own nutritional needs rather than one-size-fits-all portions.

Three-dimensional printing, long associated with prototyping plastic parts, has quietly moved into the kitchen. Food printers build edible objects layer by layer from soft, paste-like materials, much as an industrial printer builds a bracket from molten polymer. Over the past decade, food scientists have discovered that seafood, and surimi (a washed, minced fish paste) in particular, is an unusually good candidate for this technology. Its proteins form networks that behave like a natural printing ink, and the by-products of fish processing, skins, bones, and off-cuts, can be transformed into gelatins and pastes that would otherwise be discarded. Beyond conventional processing, some laboratories are going a step further, growing fish and shellfish cells directly into 3D-printed tissue that never touched the water. Together, these developments are turning 3D printing from a curiosity into a genuine tool for sustainability, customization, and food security in the seafood sector.

What Is 3D Food Printing, exactly?

Most food printers use a technique called extrusion-based printing, the same principle behind a cake-decorating piping bag, but guided by a computer. A soft, semi-solid material is loaded into a syringe or barrel, pushed through a narrow nozzle, and deposited in a pattern dictated by a digital 3D model. The machine builds the object one thin layer at a time, fusing each layer to the one below it until a complete shape emerges. Other approaches include inkjet printing, which sprays fine droplets of liquid ink, and binder jetting, which glues together layers of powder; but for seafood, extrusion is by far the dominant method because fish pastes are naturally thick and paste-like rather than liquid or powdery.

For a material to print well, it needs a delicate balance of properties. It must flow smoothly enough to be pushed through a nozzle without clogging, yet be firm enough that a freshly printed layer holds its shape and supports the weight of the layers printed on top of it. Food scientists call this balance "printability," and it depends on a material's rheology, essentially, how it flows and deforms under stress. Too runny, and the structure collapses into a puddle; too stiff, and the nozzle jams or the surface tears. Achieving this balance for a natural, variable material like fish flesh is one of the central challenges of the field.

Why Seafood? The Surimi Story

Surimi, the pale, minced, and repeatedly washed fish paste used to make familiar products like crab sticks and fish balls, turns out to be almost tailor-made for extrusion printing. When surimi is heated, its myofibrillar proteins unfold and re-link into a dense gel network, giving printed structures

their characteristic chewy, cohesive bite. Because surimi can be produced from a wide range of underused or lower-value fish species, printing it into elaborate shapes offers processors a way to raise the value of a commodity ingredient rather than selling it as an anonymous block.

A 2024 study on shrimp surimi illustrates just how sensitive the printing process is to its physical settings. Researchers systematically varied nozzle diameter, print height, print speed, and infill density to find the combination that produced the most accurate and stable structures, and found that a narrower nozzle paired with a slightly larger gap between the nozzle and the print bed allowed successive layers to fuse properly, while printing too quickly caused uneven extrusion and broken filaments. The choice of cooking method mattered just as much as the printing parameters themselves: steaming, boiling, and deep-frying caused noticeably more shape distortion than oven-baking or microwaving, and panels of tasters consistently rated the oven-baked products highest, since microwaving altered both color and texture in ways evaluators disliked (Pan et al., 2024). The lesson is a useful one for the whole field: a recipe that prints beautifully can still fall apart, quite literally, if the wrong cooking method is applied afterward.

A broader review of surimi printing research reinforces this point and extends it. Surimi alone is rarely sufficient; producers typically add structural enhancers such as salt, transglutaminase (an enzyme that stitches proteins together), or plant-derived biopolymers to strengthen the gel network and improve printing fidelity, and the technology appeals to specific groups:

children who enjoy novel shapes, elderly consumers with reduced chewing ability, and people managing dysphagia, a swallowing disorder that makes conventional textured food difficult or dangerous to eat (Diao et al., 2025). Rather than serving as a novelty act, in other words, 3D-printed surimi is increasingly being framed as a tool for inclusive nutrition, letting people who cannot manage a regular fillet still enjoy something that looks and tastes like one.

Turning Fish Waste into Printable Wonder

Perhaps the most compelling argument for seafood 3D printing is not novelty but circularity. Fish processing generates enormous volumes of skin, bones, heads, and trimmings, material that is nutritionally valuable but commercially awkward. Printing offers a way to reshape these by-products into something a consumer would actually choose to buy.

Salmon skin is a case in point. Chile, one of the world's largest salmon producers, processes hundreds of thousands of tons of salmon annually, and only a little over half of that volume is sold for direct human consumption, leaving skins and other by-products as an underused resource. A 2022 study extracted gelatin from salmon skin and tested it as a 3D printing ink at several concentrations. The researchers found that an 8% gelatin gel struck the right balance of flow and firmness: it extruded smoothly through the nozzle, yet the printed structures held their designed dimensions over time without slumping or spreading (Carvajal-Mena et al., 2022). In practical terms, a material once destined for rendering or disposal became a

food-grade printing medium capable of producing precisely shaped, stable products. Cod by-products have received similar attention. A study from Iceland used low-field nuclear magnetic resonance (LF-NMR), a technique that tracks how water molecules are distributed and move within a food, to monitor the quality of 3D-printed surimi made from cod trimmings. The researchers compared two processing routes: a modern pH-shift method, which adjusts acidity to isolate proteins, against conventional washing. They discovered that raising the salt content to 3% had a stabilizing effect on the printed surimi in both cases, and that printing with the freshest possible raw material gave the most consistent results, since longer cold storage before printing shifted how water was bound within the protein structure (Gudjónsdóttir et al., 2019). Studies like this matter because they move seafood printing beyond "can we make a shape" and toward "can we guarantee a safe, consistent, storable product," which is the real test for any commercial food technology. This waste-to-value logic extends well beyond seafood specifically. Reviews of food-industry waste valorization through 3D printing point out that shellfish shells, fruit peels, and vegetable trimmings can all be converted into printable pastes, fiber-enriched snacks, or even biodegradable packaging, with some case studies reporting meaningful reductions in waste-disposal costs and material losses when manufacturers adopt these approaches. Applying the same thinking specifically to seafood by-products, rich in collagen, minerals, and unsaturated fats, gives processors a path to squeeze considerably

more value out of every fish that comes off the boat.

Growing Fish Without the Ocean:

Bioprinting Cultured Seafood

While surimi printing reshapes existing fish tissue, an even more ambitious branch of the field is trying to grow seafood tissue from scratch, without a single fish being caught. Cultured, or "cell-based," seafood starts with cells taken from a fish or shellfish, which are then multiplied in a nutrient-rich growth medium before being assembled into a food product. 3D bioprinting offers a way to arrange these growing cells into structures that mimic the layered, fibrous architecture of a real fillet, rather than the shapeless mass produced by simple cell culture alone.

A 2024 narrative review of bioprinting for cultured meat and seafood describes this as a genuinely interdisciplinary undertaking, combining cell biology, materials science, and mechanical engineering. Researchers must select suitable cell types, formulate "bioinks" that keep cells alive and functional during and after printing, and design bioreactors that can support cell growth at a scale large enough to be commercially meaningful. The review frames the approach as a potential answer to the environmental and social costs of ever-expanding wild capture fisheries and industrial aquaculture, since it could, in principle, decouple seafood production from ocean ecosystems entirely, while candidly noting that optimizing serum-free growth media, scaling up bioreactor design, and addressing consumer trust and regulatory approval all remain significant open problems before cultured, bioprinted seafood becomes anything more than a laboratory demonstration (Gurel et al., 2024).

It is worth being clear-eyed about where this technology currently stands. Bioprinted seafood is not yet on any menu, and the cost of producing even small quantities of cultured tissue remains far higher than conventional fish. But the underlying logic, that texture and structure can be engineered layer by layer rather than grown organically inside a living animal, connects this cutting-edge research directly back to the more down-to-earth surimi printing described earlier. Both rely on the same core insight: that food architecture can be designed digitally and built physically, one thin layer at a time.

Beyond the Fillet: Personalization and Special Diets

One of the quieter but more significant promises of food printing is customization. Because a printer builds whatever shape a digital file describes, portion size, geometry, and even internal structure can be adjusted for an individual person rather than mass-produced identically for everyone. For dysphagia patients, whose swallowing difficulties are usually managed by pureeing food into unappetizing, texture-modified meals, printing offers a way to recreate the visual appeal of a normal dish, a recognizable fish shape, say, while still meeting strict internationally recognized texture standards for safe swallowing. Reviews of 3D-printed foods for this population note that adding hydrocolloids such as gums, starches, or gelatin during preparation can make otherwise unprintable ingredients printable, broadening the range of nutritious foods, including fish and other proteins, that can be safely offered to patients who might otherwise be limited to bland, unrecognizable purees.

The same underlying flexibility supports personalized nutrition more broadly. A printer can, in principle, adjust the mineral, protein, or fiber content of a printed product to match an individual's dietary needs, medical restrictions, or even athletic goals, moving food production a step closer to a "just for me" model rather than a one-size-fits-all supermarket shelf. Recent reviews of 3D food printing highlight this personalization potential alongside its role in reducing waste, framing the technology as part of a broader shift toward more digital, data-driven, and sustainable food systems (Bishta et al., 2026).

The Challenges That Remain

For all its promise, seafood 3D printing faces real obstacles before it moves from research laboratories to everyday kitchens and factories. The most fundamental is printability itself: fish tissue is a naturally variable, biological material, and its rheological behavior changes with species, freshness, fat content, and even the time of year it was caught. Formulating a consistent, reliable printing ink from such variable raw material, without leaning too heavily on additives that consumers may view with suspicion, remains an active area of research.

Sensory quality is another hurdle. A shape that prints perfectly is worthless if it does not taste, smell, or feel like food people want to eat. The shrimp surimi study discussed earlier is a reminder that even a well-optimized print can be ruined by an inappropriate cooking step, and that consumer taste panels, not just engineering metrics, must guide any final product design. Cost and throughput present a further barrier: current food printers are slow compared with conventional processing lines, and scaling from a laboratory prototype

capable of producing a single object over several minutes to an industrial process capable of feeding a supermarket supply chain is a substantial engineering leap.

Regulatory and safety questions loom particularly large for the more novel branches of the technology. Bioprinted, cell-based seafood in particular will need to clear food-safety approval processes in most countries before it can be sold, a process that is still being defined for cultured foods generally. Even for more conventional printed surimi products, ensuring consistent microbial safety, especially when raw fish pastes are stored, reformulated, and reheated through multiple processing steps, requires the kind of careful, ongoing quality-monitoring work described in the cod by-products research discussed earlier.

Looking Ahead

Despite these hurdles, the trajectory of the field points toward broader adoption rather than a passing niche. Researchers are already exploring extensions of standard 3D printing, sometimes described as 4D or 5D printing, in which printed foods are designed to change color, shape, or texture in response to cooking, moisture, or time, opening possibilities for interactive or self-transforming seafood products. Machine learning and computer-aided design tools are also beginning to appear in food-printing research, helping scientists predict which ink formulations and printing parameters will succeed without the trial-and-error of physical testing every combination.

What makes seafood particularly interesting within this wider food-printing movement is the convergence of two pressures that are unlikely to ease any time soon: rising global

demand for protein-rich, ocean-derived food, and growing awareness that a large share of every catch is currently wasted. Printing technology will not, by itself, solve either problem. But by turning trimmings into gourmet-shaped products, by making swallowing-safe meals that still look like a proper meal, and by opening a long-term path toward tissue-cultured seafood grown without a hook or a net, 3D printing gives the seafood industry a genuinely new set of tools for tackling both challenges at once.

Conclusion

Three-dimensional printing has moved seafood science well beyond its origins as a gimmick for novelty-shaped chocolates. Surimi and fish gelatin have proven to be unusually well-suited printing materials, and careful control of printing parameters and post-processing, as shown in shrimp surimi and cod by-product research, can turn them into stable, appealing, and nutritious products. By-products once considered waste, salmon skin among them, are being valorized into food-grade printing inks, while bioprinting research is laying the groundwork for seafood grown entirely outside the ocean. Challenges around consistency, taste, cost, and regulation remain substantial, but the direction of travel is clear: 3D printing is steadily becoming a practical, sustainability-minded tool for the future of seafood, not merely a laboratory curiosity.

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