Microbes and Metrics: Safeguarding Quality in Fisheries

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ABSTRACT

Fish is one of the most perishable foods, highly susceptible to microbial and chemical spoilage due to its biochemical composition. Quality assurance (QA) in fisheries, through systems like HACCP, GMP, and ISO standards, is essential for ensuring safety, extending shelf life, and maintaining consumer trust. Microbial risks include spoilage organisms such as Pseudomonas and Shewanella, and pathogens like Salmonella, Vibrio, and Listeria, while chemical and sensory metrics such as TVB-N, TMA, histamine, and odour or texture serve as key indicators of quality. Shelf-life determination combines empirical testing and predictive microbiology, with AI and machine learning enhancing accuracy. Quality failures can cause foodborne outbreaks, recalls, and economic losses, with scombrotoxin and ciguatoxin being major culprits. Emerging trends like smart packaging, AI-driven detection, and blockchain-enabled traceability are reshaping QA practices. Ultimately, consumer handling, storage, and respect for expiry dates remain critical for safeguarding fish quality and protecting public health.

INTRODUCTION

Fish is considered a highly perishable commodity due to its unique biochemical composition and vulnerability to microbial and enzymatic spoilage. Immediately after harvest, the sterile environment of fish muscle is compromised; microbes from the skin, gills, and gut rapidly colonize the tissues (Yadav *et al.*, 2025). Multiple factors contribute to this perishability: fish has a high-water activity, neutral-to-slightly alkaline pH, rich non-protein nitrogenous compounds, and delicate unsaturated fats, creating an ideal environment for rapid microbial proliferation and chemical changes. The process of spoilage leads to undesired changes in appearance, texture, odour, and flavour, with the formation of volatile amines and other compounds that can render fish unfit for consumption and potentially hazardous to health (Yadav *et al.*, 2025). Given the susceptibility of fish to rapid degradation, robust quality assurance systems are indispensable in the fisheries sector. Quality assurance encompasses strategies like Hazard Analysis and Critical Control Points (HACCP), Good Manufacturing Practices (GMP), and adherence to internationally recognized standards such as ISO 9000 (Chakraborty and Rout, 2025). These systems are critical not only for minimizing food-borne illness risks and reducing post-harvest losses, but also for meeting regulatory requirements and consumer expectations for safety and freshness.

Effective quality control ensures the delivery of safe and nutritious seafood by monitoring the entire supply chain from harvesting through processing, storage, and distribution (Fig. 1). With the globalization of seafood trade, quality assurance is also essential for maintaining market credibility, legal compliance, and reducing customer complaints, thus safeguarding the economic viability of fisheries and fish processing enterprises. In immediate, the high perishability of fish demands rigorous quality assurance measures to protect consumer health, maintain product integrity, and sustain trust and competitiveness in the global market (Yeşilsu *et al.*, 2025). This article highlights the microbial risks and quality metrics critical for fish safety, methods for determining shelf-life, and the consequences of quality failures. It also explores emerging technologies such as smart packaging, AI, and blockchain, while emphasizing the role of consumers in maintaining quality. Overall, quality assurance serves as a key safeguard for both industry and public health.

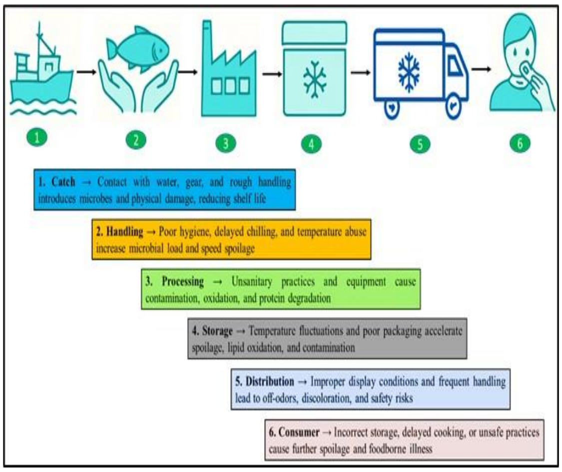

Fig. 1 Stages from Catch to Consumption and Their causes and impact on Fish Quality

Microbial Risks in Fish and Fish Products

Fish and fish products are among the most perishable foods due to their rich nutrient content, high water activity, and near-neutral pH, all of which create an ideal environment for microbial proliferation. The associated microorganisms can be broadly categorized into spoilage organisms and pathogenic organisms, each contributing differently to quality loss and food safety risks (Table 1). Spoilage bacteria such as *Pseudomonas spp.* dominate under chilled aerobic storage, producing volatile bases like trimethylamine that impart a strong fishy odour, while *Shewanella putrefaciens* generates hydrogen sulphide and sulphurous compounds that cause off-odours in marine fish (Parlapani *et al*., 2024). Other key spoilage organisms include *Aeromonas*, *Brochothrix thermosphacta*, and *Photobacterium phosphoreum*, particularly in vacuum-packed products. On the other hand, pathogenic bacteria directly threaten public health. *Salmonella spp.*, often introduced through contaminated water or poor handling, cause gastrointestinal infections; *Vibrio parahaemolyticus* and *V. vulnificus*, naturally occurring in marine environments, are linked to severe illness from raw or undercooked seafood (Salama & Chennaoui, 2024); and *Listeria monocytogenes*, capable of growing at refrigeration temperatures, is a major hazard in smoked and ready-to-eat fish. Additionally, *Clostridium botulinum* type E poses risks under anaerobic storage, while *Escherichia coli* serves as an indicator of faecal contamination.

Processed fish products also exhibit distinct microbial shifts. In surimi, typical microflora includes *Moraxella*, pseudomonads, and *Corynebacterium*. Smoking alters the microbial profile: hot smoking suppresses Gram-negative bacteria but favours Gram-positive species like micrococci and *Corynebacterium*, whereas cold smoking allows *Pseudomonas* growth. Traditional preservation methods such as salting and drying further introduce fungal contaminants, with molds like *Aspergillus niger*, *A. flavus*, and *Penicillium spp.* commonly found in dried fish. Besides microbial spoilage, dried products are prone to chemical deterioration, particularly lipid oxidation in fatty species, which leads to rancidity and quality loss (da Silva, 2019). Even canned fish, though considered shelf-stable, may suffer microbial spoilage if improperly processed or stored, with pathogens such as *Salmonella*, *Clostridium botulinum*, and *Listeria monocytogenes*, as well as spoilage bacteria including *Pseudomonas*, *Shewanella*, and lactic acid bacteria, being the main concerns (Yadav *et al*., 2025).

Table 1 Major Spoilage vs. Pathogenic Organisms in Fish

Organism	Source	Effect on Fish	Health Risk (Y/N)
Pseudomonas spp.	Water, surfaces, handling	Off-odour, slime, soft texture	N
Shewanella putrefaciens	Marine environment	Hydrogen sulphide, sulphurous smell	N
Aeromonas spp.	Freshwater, ice	Spoilage, discoloration	N
Salmonella spp.	Contaminated water, hygiene	No spoilage; causes foodborne illness	Y
Vibrio parahaemolyticus	Marine waters	No spoilage; gastroenteritis	Y
Listeria monocytogenes	Processing plants	No spoilage; listeriosis	Y
Clostridium botulinum E	Anaerobic storage	No spoilage; toxin production	Y
E. coli	Faecal contamination	Indicator organism	Y (opportunistic)

Key Metrics in Fish Quality Assurance

Key metrics in fish quality assurance rely on a combination of microbiological, chemical, and sensory indicators that collectively determine freshness, safety, and consumer acceptability. Microbiological tests, such as total viable counts (TVC), provide an overall measure of microbial load, while coliforms and *E. coli* serve as indicators of hygiene and possible faecal contamination. Specific pathogen testing for *Salmonella*, *Vibrio*, *Listeria monocytogenes*, and *Clostridium botulinum* ensures compliance with food safety standards (Wetuhafifa, 2017). Chemical parameters offer valuable insight into spoilage processes, with total volatile basic nitrogen (TVB-N) reflecting microbial and enzymatic breakdown of proteins, trimethylamine (TMA) indicating bacterial activity in marine fish, and biogenic amines like histamine acting as both spoilage markers and safety concerns in species such as tuna and mackerel (Bekhit *et al*., 2021). Sensory evaluation, though subjective, remains vital for rapid assessment, as consumers rely heavily on odour, gill colour, and texture to judge freshness; bright red gills, firm flesh, and clear eyes signify quality, whereas discoloured gills, soft texture, and sour or sulphurous odours indicate spoilage. Together, these microbiological, chemical, and sensory metrics provide a comprehensive framework for monitoring quality, determining shelf life, and safeguarding consumer health.

Table 2 Comprehensive Indicators for Fish Quality Assessment (Chemical, Microbial, and Sensory Parameters)

Parameter	Basis / Compound Measured	Indicator of	Acceptability / Threshold
Total Volatile Bases (TVB-N)	Ammonia, TMA, DMA from microbial spoilage	General spoilage index	Fresh fish: <20 mg% Limit: 35–40 mg/100 g muscle
Trimethylamine (TMA-N)	Bacterial reduction of TMAO	Specific spoilage indicator	10–15 mg/100 g muscle = limit of acceptability
Histamine	Decarboxylation of histidine by bacteria (e.g., in tuna, mackerel, sardine)	Scombroid poisoning risk	< 50 mg/Kg
Indole	Produced during shrimp decomposition	Spoilage in shrimp/prawns	<25 µg/100 g muscle = acceptable
Nucleotide degradation products	ATP breakdown to IMP, inosine, hypoxanthine	Freshness loss	High IMP = fresh High inosine/Hx = spoilage
Hypoxanthine (Hx)	Measured by absorbance at 290 nm	Spoilage progression	>2.5 µmol/g = spoiled
K-value	Ratio of inosine + hypoxanthine to total nucleotides (%)	Freshness indicator	Fresh fish: 20–25% Rejection: 50–60%
Peroxide Value (PV)	Peroxides, hydroperoxides (primary lipid oxidation)	Oxidative rancidity onset	Fresh oil ≤ 1 meq O_2/kg Spoiled: up to 10 meq/kg
Thiobarbituric Acid Value (TBA)	Malonaldehyde (secondary lipid oxidation)	Rancidity progression	Increases with storage; complements PV
Microbial Counts (TVC, coliforms, Vibrio test)	Enumeration of total bacteria and pathogens	Hygiene, spoilage, safety	TVC < 10^5–10^6 CFU/g (acceptability) Absence of *Salmonella*, *Listeria*, pathogenic *Vibrio*

Parameter	Basis / Compound Measured	Indicator of	Acceptability / Threshold
Sensory Assessment	Odour, gill colour, texture, eye clarity	Overall freshness & consumer acceptability	Bright red gills, firm flesh, clear eyes = fresh Off-odour, discoloured gills, soft/slimy flesh = spoiled

Determining Shelf-life and Expiry Dates

The shelf life of fish and fish products is defined as the time during which they remain safe for consumption and retain acceptable sensory, nutritional, and functional qualities under specified storage conditions. Since fish is highly perishable due to its high-water activity, neutral pH, and nutrient-rich composition, accurate determination of shelf life is essential for ensuring food safety, consumer confidence, and reducing food waste. **Shelf-life testing** is commonly carried out under different storage conditions, such as chilled, frozen, modified atmosphere, or ambient environments. During these trials, microbiological parameters (total viable counts, specific spoilage organisms, and pathogens), chemical indicators (total volatile basic nitrogen, trimethylamine, lipid oxidation products), and sensory attributes (odour, texture, colour) are monitored over time (Calligaris *et al*., 2019). The point at which the product no longer meets quality or safety standards defines its shelf life. Challenge testing, where products are inoculated with specific pathogens under controlled conditions, may also be performed to validate microbial safety. **"Use By" dates** indicate the last safe day of consumption and are applied to highly perishable products like fresh or smoked fish. **"Best Before" dates** relate to quality rather than safety, marking the period when the product is at its optimal condition but may still be consumed after with reduced quality. Clear labelling helps consumers make informed decisions and prevents both health risks and unnecessary food waste.

Predictive Microbiology

In addition to empirical testing, predictive microbiology and mathematical modelling are increasingly applied to estimate shelf life. These models simulate microbial growth and spoilage kinetics under varying temperature, pH, water activity, and packaging conditions, helping predict the time at which spoilage or safety thresholds are exceeded. Predictive tools allow for scenario testing (e.g., temperature abuse during distribution) and support regulatory compliance, making them valuable complements to traditional shelf-life studies (Tarlak *et al*., 2023). Predictive microbiology uses mathematical models and computational tools to describe and forecast microbial behaviour in food systems, thereby enabling researchers, industries, and regulators to assess risks and design effective control measures. At its core, it relies on **primary models** (e.g., Gompertz, logistic, Baranyi, Huang) that describe microbial growth over time, and **secondary models** (e.g., Ratkowsky, Arrhenius) that relate growth parameters to environmental factors. Together, these models provide insights into microbial behaviour under both constant and fluctuating storage conditions (Tarlak *et al*., 2023).

One of the most important applications is **shelf-life estimation**. By simulating microbial proliferation, predictive models identify how long fish or other perishable foods remain safe and acceptable. For example, studies modelling the growth of *Pseudomonas spp.* in fish, poultry, and shrimp across different temperatures show strong correlations between microbial dynamics and spoilage onset. Such models are also integrated into **risk assessments**, where "what-if" scenarios can be evaluated without extensive experimental trials (García *et al*., 2019). Recent advances include the **one-step modelling approach,** which integrates primary and secondary models simultaneously, and the application of **machine learning (ML)** techniques such as random forests, support vector regression, and neural networks. These approaches offer higher accuracy and can handle complex, nonlinear interactions among multiple variables.

Consequences of Quality Failures

Quality failures in fish and fish products can result in significant public health risks and major economic losses for the seafood industry. Outbreak data illustrate the severe consequences of inadequate quality control, particularly in relation to bacterial and toxin-related illnesses. Between 2012 and 2021, five confirmed multistate Salmonella outbreaks in the United States, linked to fish and fishery products (excluding raw molluscan shellfish), caused 633 illnesses and 92 hospitalizations. An additional four outbreaks, involving 88 illnesses and 12 hospitalizations, implicated fish as a suspect vehicle (Viazis *et al*., 2025).

Each year in the U.S., an estimated 260,000 people fall ill from contaminated fish, making fish the most commonly implicated food category in outbreaks. An analysis of the CDC Foodborne Disease Outbreak Surveillance System for 1998–2015 reported 857 fish-associated outbreaks, leading to 4,815 illnesses, 359 hospitalizations, and 4 deaths (Barrett *et al*., 2017). The average annual number of outbreaks declined from 62 (1998–2006) to 34 (2007–2015), suggesting some progress but highlighting ongoing risks. Hawaii (26%) and Florida (24%) reported the highest outbreak frequencies. Among confirmed etiologies, scombrotoxin (55%) and ciguatoxin (36%) dominated, followed by Salmonella (26% of illnesses). Scombrotoxin and tuna accounted for 223 outbreaks and 720 illnesses, while Salmonella and tuna caused 660 illnesses. Norovirus and Salmonella were responsible for the largest outbreaks, sometimes involving hundreds of cases. Restaurants were the most common preparation sites (52%), followed by private homes (33%).

A fish recall is the urgent withdrawal of unsafe or contaminated fish products from the market, initiated by companies or mandated by regulatory agencies such as the FDA to protect consumer health. Recalls may involve fresh, frozen, canned, or processed fish and are commonly triggered by bacterial contamination (e.g., *Salmonella*, *Listeria*), histamine poisoning in species like tuna and mackerel, chemical contaminants such as mercury or PCBs, undeclared allergens, or foreign material contamination. The FDA manages recalls through inspections, product testing, classification into Class I (high risk), Class II (moderate risk), or Class III (low risk), and issuing public alerts alongside corrective actions (Blickem *et al*., 2023). While recalls are essential for safety, they cause financial losses, damage brand reputation, disrupt supply chains, and increase regulatory scrutiny for producers. To prevent such incidents, fish processors must adopt Good Manufacturing Practices (GMP), maintain strict cold chain management, conduct microbial and chemical testing, ensure allergen control and accurate labelling, implement foreign material detection systems, and establish supplier verification and traceability. These proactive measures not only reduce recall risks but also protect consumer trust and ensure stability within the seafood industry (Blickem *et al*., 2023; Robinson, 2025).

Economically, the financial losses encompass direct recall costs often millions of dollars as well as lost sales and legal liabilities. Perhaps more damaging is reputational harm, as brands may experience lasting erosion of consumer confidence that affects market share. Companies may face heightened regulatory scrutiny and operational restrictions after such events, adding to ongoing costs. Prevention via quality assurance is essential not only for food safety but also to safeguard the industry's economic sustainability and brand integrity.

Emerging Trends in Fish Quality Assurance

Smart packaging involves the integration of sensors and indicators into packaging materials to monitor fish freshness in real-time. These packages respond to environmental conditions such as temperature, pH, and microbial growth by changing color or providing electronic signals. For example, nano-encapsulated pH indicators in packaging films can visually alert consumers and retailers to spoilage through colour changes, improving transparency and reducing food waste. Such interactive packaging helps ensure fish quality is maintained throughout the supply chain by providing immediate feedback on product freshness (Ibrahim *et al*., 2021). Artificial intelligence (AI) and machine learning technologies have been developed to detect fish diseases and microbial contamination quickly and accurately. Using deep learning algorithms like convolutional neural networks (CNNs) on image data or spectral data, these systems can identify fish health status and microbial spoilage non-destructively. This enables early intervention in aquaculture and processing, reducing losses and ensuring better safety standards. AI applications also extend to automated monitoring of water quality parameters critical for preventing fish diseases (Tripathi *et al*., 2024). Blockchain technology is revolutionizing seafood traceability by providing an immutable, transparent ledger of fish products' journey from catch to consumer. It enhances supply chain transparency, helps verify origin and sustainability claims, and mitigates illegal, unreported, and unregulated (IUU) fishing. Blockchain facilitates faster recall management, improves consumer trust, and enables regulatory compliance by securely documenting each transaction and handling step in the fish supply chain (Gawai, 2025).

Role of Consumers in Quality Assurance

Consumers play a vital role in ensuring fish quality and safety through proper storage, handling, and respecting expiry dates. Even with stringent controls in harvesting, processing, and distribution, the final responsibility often lies with the consumer to maintain fish quality until consumption. Proper storage, primarily maintaining cold chain integrity, is essential to slow down microbial growth and chemical spoilage. Fish should be refrigerated at temperatures close to 0°C or frozen if not consumed immediately. Inadequate refrigeration can lead to rapid spoilage, off-odours, and loss of nutritional value (Hicks, 2016). Handling practices at home also influence the final quality and safety of fish. Consumers must avoid cross-contamination by using clean utensils and surfaces while preparing fish. Thawing frozen fish properly and cooking to recommended temperatures effectively reduce health risks from pathogens (Hicks, 2016). Respecting expiry or "best before" dates is critical because these dates reflect the shelf life determined under ideal storage conditions. Consuming fish past these dates increases the risk of foodborne illness and degraded sensory quality. Awareness and adherence to these safety cues are crucial to prevent illness and food wastage.

CONCLUSION

Quality assurance is essential for safeguarding both the fish industry and consumers by ensuring seafood safety, quality, and integrity across the supply chain. For the industry, strong systems like HACCP, ISO standards, and Good Manufacturing Practices reduce contamination risks, spoilage, recalls, and legal liabilities, while improving efficiency, product consistency, and global market access. Certified quality also boosts reputation and customer trust. For consumers, quality assurance ensures fish is safe, fresh, and nutritious, free from harmful pathogens and contaminants. It protects public health, preserves sensory appeal, and prevents foodborne illness. Proper handling and storage by consumers further support quality from catch to plate.

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