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MICROBIAL SPOILAGE AND QUALITY DETERIORATION IN FISH: PROCESSING STRATEGIES FOR CONTROL AND MITIGATION – A REVIEW

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Abstract: Fish and fishery products are highly perishable commodities due to their high moisture content, neutral pH, autolytic enzyme activity, and rapid proliferation of spoilage microorganisms. Microbial spoilage and biochemical deterioration significantly reduce shelf life, compromise safety, and result in substantial economic losses, particularly in tropical regions. The present review critically examines mechanisms of microbial spoilage, dominant specific spoilage organisms (SSOs), biochemical indicators of quality deterioration, and environmental factors influencing spoilage progression. The metabolic activities of psychrotrophic bacteria such as *Pseudomonas spp.*, *Shewanella putrefaciens*, *Photobacterium phosphoreum*, *Vibrio spp.*, and lactic acid bacteria are discussed in relation to production of trimethylamine, total volatile base nitrogen, hydrogen sulfide, and biogenic amines. Conventional preservation methods including icing, chilling, freezing, drying, salting, smoking, and thermal processing are evaluated along with emerging non-thermal technologies such as modified atmosphere packaging, high-pressure processing, cold plasma, ozone treatment, and natural bio-preservatives. Integration of hurdle technology, predictive microbiology, digital cold chain monitoring, and smart packaging systems is highlighted as an effective strategy for spoilage mitigation. The review emphasizes the need for improved hygiene practices, infrastructure strengthening, and adoption of advanced processing technologies to enhance shelf life, safety, and market competitiveness of fish products.

Keywords: Microbial spoilage; fish quality; psychrotrophic bacteria; SSOs; biogenic amines; non-thermal processing; shelf life.

1. Introduction

Fish constitutes an important component of human nutrition due to its high quality protein, essential amino acids and polyunsaturated fatty acids. According to FAO (2023), global fish production has reached unprecedented levels, with aquaculture contributing substantially to total output. India ranks among the leading fish producing nations, with rapid growth in inland aquaculture and marine fisheries sectors (MPEDA, 2023).

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Despite production growth, fish remains highly perishable. Immediately after death, biochemical changes such as ATP degradation, autolysis and lipid oxidation begin, leading to quality deterioration (Huss, 1995). The high moisture content (70–80%), neutral pH and abundance of non-protein nitrogenous compounds create favourable conditions for microbial growth (Gram and Dalgaard, 2002). Under tropical Indian conditions, spoilage may occur within 8–12 hours without proper icing.

Microbial spoilage accounts for major post-harvest losses in India, estimated between 10–25% depending on region and infrastructure (ICAR-CIFT, 2022). Parlapani et al., (2020) highlighted the role of specific spoilage organisms (SSOs) in fresh fish deterioration during chilled storage. Recent research also emphasizes formation of biogenic amines such as histamine, posing public health concerns (EFSA, 2023).

Effective control of spoilage is therefore essential to ensure food safety, reduce losses and improve export competitiveness of Indian seafood.

2. Microbial Ecology and Specific Spoilage Organisms (SSOs)

Fresh fish harbor diverse microbiota; however, only certain species dominate during storage and cause spoilage.

2.1 Dominant SSOs in Fish

Gram and Dalgaard (2002) defined SSOs as microorganisms that produce metabolites responsible for off-odors and sensory rejection. Under aerobic chilled storage, Pseudomonas spp. dominate due to their strong proteolytic and lipolytic activity. In marine fish, Shewanella putrefaciens contributes to hydrogen sulfide production. Under modified atmosphere packaging, Photobacterium phosphoreum becomes predominant (Sivertsvik et al., 2021).

In Indian marine species, Vibrio spp. are frequently encountered due to warm coastal waters (Jeyasekaran et al., 2021).

Table 1. Major Specific Spoilage Organisms and Metabolites in Fish

SSO	Storage Condition	Major Metabolites	Spoilage Effect
Pseudomonas spp.	Aerobic chilled	TMA, ammonia	Off-odor
Shewanella putrefaciens	Marine fish	H_2S	Sulfur smell
Photobacterium phosphoreum	MAP storage	TMA	Fishy odor
Vibrio spp.	Marine environment	Proteases	Texture softening
Lactic acid bacteria	Vacuum packed	Organic acids	Sour odor

Recent genomic studies (Li et al., 2023) show that SSOs possess specialized metabolic pathways enabling efficient degradation of TMAO and amino acids.

3. Biochemical Indicators of Spoilage

Assessment of fish quality is a multidimensional process involving microbiological, chemical and sensory evaluation. While sensory attributes such as odor, texture and appearance provide immediate indicators of freshness, biochemical and chemical indices offer objective and quantifiable measures of spoilage progression. During storage, enzymatic autolysis, microbial metabolism and lipid oxidation lead to accumulation of specific chemical compounds that serve as reliable spoilage indicators. Among these, Total Volatile Base Nitrogen (TVB-N), Trimethylamine (TMA), biogenic amines and lipid oxidation parameters are widely used in quality evaluation of fish and fishery products.

3.1 Total Volatile Base Nitrogen (TVB-N)

Total Volatile Base Nitrogen (TVB-N) is one of the most widely accepted chemical indices for assessing fish spoilage. It represents the cumulative concentration of volatile basic nitrogenous compounds such as ammonia, dimethylamine (DMA) and trimethylamine (TMA), which are produced as a result of microbial and enzymatic degradation of proteins and non-protein nitrogenous constituents (Connell, 1980).

In fresh fish, TVB-N levels are relatively low; however, during storage—particularly under inadequate refrigeration—microbial deamination and decarboxylation reactions accelerate, leading to rapid accumulation of volatile bases. The rate of increase in TVB-N is influenced by species, storage temperature, microbial load and handling practices. Marine species rich in trimethylamine oxide (TMAO) tend to show a faster rise in TVB-N compared to freshwater species.

3.2 Trimethylamine (TMA)

Trimethylamine (TMA) is a key spoilage metabolite formed through bacterial reduction of trimethylamine oxide (TMAO), a naturally occurring compound abundant in marine fish. Specific spoilage organisms such as Shewanella and certain Pseudomonas species possess TMAO reductase enzymes that convert TMAO into TMA during storage, particularly under chilled and aerobic conditions (Dalgaard, 2000).

TMA accumulation is closely associated with the development of the characteristic "fishy" or ammonia-like odor in spoiled fish. Since TMA is a volatile compound, its concentration correlates well with sensory deterioration. In the early stages of storage, TMA levels remain minimal; however, as microbial populations reach spoilage levels (approximately 10^7–10^8 cfu/g), TMA increases significantly.

3.3 Biogenic Amines

Biogenic amines are low-molecular-weight organic nitrogenous compounds formed mainly by microbial decarboxylation of free amino acids during storage. Among them, histamine is of major concern in scombroid fishes such as mackerel, tuna and sardine due to its association with scombroid poisoning.

Histamine is produced from the amino acid histidine by histidine decarboxylase-producing bacteria under temperature abuse conditions. Unlike other spoilage indicators, histamine formation may occur even when sensory attributes appear acceptable, thereby posing serious food safety risks. Symptoms of histamine intoxication include flushing, headache, nausea and allergic-like reactions.

The European Food Safety Authority (EFSA, 2023) recommends strict monitoring of histamine levels, maintaining concentrations below 50 mg/kg in fishery products intended for human consumption. Apart from histamine, other biogenic amines such as putrescine and cadaverine contribute to off-odors and may potentiate histamine toxicity.

Control of biogenic amine formation is therefore critically dependent on rapid chilling, hygienic handling and maintenance of an uninterrupted cold chain from harvest to retail.

Table 2. Important Quality Indicators and Acceptable Limits

Indicator	Acceptable Limit	Significance
TVB-N	25–35 mg/100g	Protein degradation
TMA	10–15 mg/100g	Microbial spoilage
Histamine	<50 mg/kg	Safety parameter
K-value	<60%	Freshness index
Peroxide Value	<10 meq/kg	Lipid oxidation

Recent 2024 studies recommend combining microbial counts with metabolomics for accurate shelf-life prediction (Wang, H. et al., 2024).

4. Factors Influencing Spoilage

- Temperature abuse
- Initial microbial load
- Oxygen availability
- Handling stress
- Fat content

In many Indian landing centers, delayed icing and exposure to sunlight increase microbial growth (ICAR-CIFT, 2022). Lack of insulated transport further exacerbates deterioration.

5. Conventional Processing Strategies

5.1 Icing and Chilling

Rapid chilling to 0–4°C significantly slows microbial growth (Huss, 1995). Proper icing can extend shelf life up to 10–15 days in certain marine species.

5.2 Freezing

Freezing at −18°C inhibits microbial proliferation but may cause protein denaturation and drip loss (Venugopal, 2022).

5.3 Drying and Salting

Traditional sun drying remains common along Indian coasts. However, contamination and uneven drying affect quality (Joseph et al., 1988).

5.4 Smoking

Smoking provides antimicrobial phenolic compounds and reduces water activity.

6. Emerging Technologies

6.1 Modified Atmosphere Packaging (MAP)

High CO_2 concentration inhibits aerobic bacteria and extends chilled shelf life (Sivertsvik et al., 2021).

6.2 High Pressure Processing (HPP)

HPP inactivates microorganisms without significant thermal damage (Rastogi et al., 2007).

6.3 Cold Plasma and Ozone

Recent studies demonstrate significant microbial reduction using cold plasma (Misra et al., 2023).

6.4 Natural Bio-preservatives

Plant extracts, bacteriocins and chitosan coatings show antimicrobial activity (Benjakul, 2023).

Table 3. Comparison of Emerging Preservation Technologies

Technology	Mechanism	Advantage	Limitation
MAP	CO_2 inhibition	Shelf-life extension	Package cost
HPP	Pressure inactivation	Nutrient retention	High investment
Cold Plasma	Reactive species	Surface sterilization	Limited penetration
Ozone	Oxidative effect	Eco-friendly	Equipment requirement

7. Hurdle Technology and Digital Monitoring

Leistner (2000) proposed hurdle technology combining multiple preservation factors. Integration of temperature control, MAP and natural preservatives enhances stability.

Digital cold chain monitoring using IoT devices is gaining importance in Indian seafood export sector (Kamble et al., 2022).

8. Challenges and Future Perspectives

Despite significant advancements in fish preservation and processing technologies, several challenges continue to limit effective control of microbial spoilage, particularly in developing countries such as India.

One of the major constraints is the existence of cold chain gaps across the supply chain. Inadequate icing practices at landing centers, insufficient refrigerated transport facilities and poor temperature control during retail display contribute significantly to rapid microbial proliferation. Temperature fluctuations accelerate enzymatic and microbial activity, thereby reducing shelf life and increasing economic losses. Strengthening integrated cold chain infrastructure and real-time temperature monitoring systems remains a priority for ensuring quality retention.

The emergence of antibiotic-resistant bacteria in aquatic environments presents another growing concern. Indiscriminate use of antibiotics in aquaculture can promote resistant strains that not only affect product safety but also pose public health risks. Spoilage organisms harboring resistance traits may exhibit increased survival under processing stresses, complicating microbial control strategies. Therefore, responsible antibiotic stewardship and development of alternative antimicrobial approaches are essential.

There is an increasing demand for smart and active packaging systems capable of monitoring and extending product freshness. Intelligent packaging incorporating freshness indicators, time–temperature integrators and antimicrobial coatings can provide real-time quality information to processors and consumers. However, cost constraints and limited commercial adoption currently restrict large-scale implementation, especially in small-scale fisheries sectors.

Development of predictive microbiology models offers promising opportunities for estimating shelf life and microbial growth under varying storage conditions. Mathematical models integrating temperature, pH, water activity and packaging atmosphere can help processors optimize storage strategies and minimize spoilage. However, region-specific data and validation under Indian climatic conditions are still limited and require further research.

Another emerging focus area is sustainable waste utilization. Spoiled or processing discards contribute substantially to environmental pollution. Conversion of fish waste into value-added products such as fish protein hydrolysates, bioactive peptides, silage, collagen and biofertilizers aligns with circular bioeconomy principles and reduces resource wastage. Efficient integration of waste valorization technologies can enhance economic sustainability of the fisheries sector. Future research should emphasize the integration of artificial intelligence (AI)-based spoilage prediction systems, advanced biosensors for rapid detection of spoilage metabolites, and digital cold chain tracking platforms. Development of cost-effective freshness biosensors capable of detecting TMA, TVB-N or biogenic amines in real time would significantly improve quality assurance. Furthermore, incorporation of circular bioeconomy approaches into fish processing systems can promote sustainability while minimizing environmental impact.

Overall, a multidisciplinary approach combining advanced processing technologies, digital tools, regulatory enforcement and sustainable practices is essential for effective control and mitigation of microbial spoilage in fish and fishery products.

9. Conclusion

Microbial spoilage remains the primary cause of fish quality deterioration. Integrated control strategies combining hygienic handling, temperature control, advanced processing technologies, and real-time monitoring systems are essential for ensuring safety and extending shelf life. Adoption of innovative preservation approaches and strengthening infrastructure will significantly reduce post-harvest losses and enhance global competitiveness.

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