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Recent advances in fish freezing technologies and cold chain management: Ensuring quality from catch to consumer

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Abstract
Recent advances in fish freezing and cold chain technologies have greatly improved the preservation of quality, safety and nutritional value in aquatic products. Traditional freshness evaluation methods are often invasive and time-consuming, but innovative sensor technologies now enable non-invasive, real-time monitoring of spoilage indicators such as volatile compounds and biochemical changes. This review highlights cutting-edge freezing methods like Individually Quick Freezing (IQF), super-chilling, cryogenic and ultrasound-assisted freezing, which enhance texture, reduce nutrient loss and extend shelf life. Additionally, smart sensors, IoT-based systems and advanced packaging are transforming cold chain logistics by improving traceability and quality control. Case studies from leading seafood sectors illustrate best practices, while challenges such as energy use and environmental concerns are addressed. By integrating technological and logistical innovations, the seafood industry can significantly reduce post-harvest losses and ensure food safety, offering valuable insights for future research and sustainable development in global fishery supply chains.

Keywords: IQF, freezing, biosensors, cold chain management, quality, seafood supply chain, temperature control, cold chain logistics

1. Introduction

Fish freezing is one of the most widely employed preservation techniques to maintain the freshness, quality and safety of fishery products. By significantly slowing down microbial activity and biochemical degradation, freezing enables long-term storage and facilitates extended transportation, ensuring that fish remains safe and suitable for consumption over time (Smuts *et al*., 2025) [49]. Freezing is a critical preservation method in the seafood industry, widely utilized to increase the shelf life of fish, inhibit spoilage and retain its nutritional and sensory qualities. This method is crucial for maintaining the safety and quality of fishery products during processing, storage and distribution. In the worldwide fish supply chain, preserving the freshness of fish from catch to consumer is essential for ensuring the quality and safety. Fish cold rooms play a pivotal role in this process, as they are essential for preserving the quality of fish and preventing spoilage (Hanafiah *et al.*, 2024) [15]. From the fishing vessel to retail shelves, the use of cold storage is an indispensable part of the journey, ensuring that fish remains fresh, safe and nutritious. Cold chain management is crucial for preserving the freshness, quality and safety of fish. Proper temperature control throughout the supply chain from catch to consumer prevents bacterial growth, slows enzymatic spoilage and ensures that fish remains safe to eat. Aquatic products represent a vital segment of the worldwide food distribution network, offering high nutritional value and contributing significantly to the worldwide economy. However, their highly perishable nature poses substantial challenges, as freshness deterioration can adversely impact sensory qualities, nutritional content and more critically, consumer health especially amid rising concerns over food-borne illnesses (Ren *et al*., 2022) [41].

In recent decades, maintaining the quality of aquatic products through refrigerated supply systems has remained a constant difficulty. Maintaining stable cold conditions throughout transport and storage remains crucial, as even minor temperature fluctuations can accelerate spoilage and significantly compromise product freshness and quality (Liu *et al*., 2023) [27]. Moreover, non-destructive testing technologies are essential for monitoring freshness and maintaining quality control within cold chain logistics, offering rapid, reliable and non-invasive assessment of aquatic products throughout the supply chain.

Recently, cutting-edge flexible sensor technologies have been increasingly utilized for evaluating freshness, providing innovative, immediate and non-intrusive methods for tracking the quality of aquatic products (Huang *et al*., 2024) [60]. Compared to conventional sensors used for freshness evaluation, flexible sensors offer enhanced monitoring accuracy and faster response times, significantly improving real-time quality assessment in temperature-controlled supply chain logistics (Huang *et al*., 2024) [60]. Significantly, the development and deployment of advanced sensor technologies have catalyzed the emergence of integrated multifunctional sensing systems. This convergence has significantly enhanced operational efficiency within cold chain logistics and paved the way for the realization of intelligent, automated cold chain management (Zhou *et al.*, 2022) [68]. In this review the critical role of fish freezing and cold chain management to emphasize their importance for economic efficiency and global distribution within the fish industry.

2. Principles of fish freezing

The freezing process converts tissue water into ice crystals, with nucleation rate and crystal growth dictated by thermal gradients. Rapid freezing induces numerous small intracellular ice crystals, preserving cellular integrity, while slow freezing promotes large extracellular crystals that puncture cell membranes, causing drip loss and texture degradation during thawing (Zhu *et al*., 2023) [70]. Protein denaturation driven by dehydration, ice mechanical damage and concentration of solutes alters myofibrillar protein structure, reducing water-holding capacity by up to 25% in slow-frozen fish (Ramezani *et al*., 2024) [39]. Lipid oxidation accelerates in frozen fatty species (e.g., mackerel, salmon) due to enzymatic activity (lipoxygenases) and metal ion catalysis, generating off-flavors (Karoui *et al*., 2024) [21].

2.1 Types of Freezing Methods

2.1.1 Air Blast Freezing

Forced-air tunnels (-30°C to -40°C) achieve freezing rates of 0.5-2 cm/h, suitable for whole fish or blocks. However, uneven heat transfer and surface dehydration (~2-5% weight loss) remain limitations. Recent advances include impingement technology (high-velocity jets enhancing surface heat transfer by 30-50%) and humidified air systems reducing dehydration by 60% (Li *et al*., 2022) [25].

2.1.2 Plate Freezing

Direct contact between fish and refrigerated plates (-35°C) enables efficient heat transfer (freezing rates: 1-5 cm/h), ideal for fillets or packaged products. Innovations include flexible contact plates accommodating irregular shapes and variable pressure control minimizing gaps, improving yield by 15% (Nielsen *et al.*, 2024) [32].

2.1.3 Cryogenic Freezing

Immersion/spraying with liquid nitrogen (-196°C) or CO_2 (-78°C) achieves ultra-rapid freezing (>10 cm/h), producing micron-scale ice crystals. This method reduces drip loss by 40% compared to air freezing but faces scalability challenges due to high operational costs (Zhang *et al*., 2022) [66].

2.1.4 Individual Quick Freezing (IQF)

Combines fluidized beds (for small products like shrimp) or air blast (for fillets) to freeze items separately, preventing clumping. Modern IQF systems integrate cryogenics for crust freezing followed by air freezing, optimizing energy use while maintaining product individuality (Duan *et al*., 2022) [9-10].

3. Cold Chain Mamagement in Fisheries

3.1 Components of cold chain

Table 1: Represents components of cold chain

Component	Key Requirements	Technological Advances	References
On-board Handling	Immediate chilling (0°C to -1°C) within 2 hrs; Ice:fish ratio ≥1:1	Slurry ice systems with antimicrobial additives; Insulated fish holds with rapid cooling	Wang *et al.* (2024); FAO (2024) [61, 11]
Land-based Processing	Freezing to -35°C within 4 hrs post-landing; Hygienic processing line	Automated grading/gutting; Cryogenic crust freezing (-60°C) for sashimi-grade tuna	Zhu *et al.* (2023) [69]; Zhang *et al.* (2024) [70]
Storage	Lean fish: -30°C; Fatty fish: -24°C; RH >95%	AI-driven defrost cycles; Phase-change materials (PCMs) for temperature stability	Li *et al.* (2022) [25]; Liu *et al.* (2023) [27]
Transportation	±1°C stability; Vibration <1.5 g	IoT-enabled containers with blockchain traceability; RFID/TTI sensors	Zhang *et al.* (2024) [69]
Retail Display	Closed cabinets: -18°C ± 0.5°C; Defrost cycles <3x/day	LED-lit closed cabinets with UV filters; PCM-enhanced shelving	Badia-Melis *et al.* (2023) [4]
Consumer Handling	Home storage at ≤-18°C; Thawing at 4°C	Insulated delivery boxes with dry ice/PCMs; Smart labels indicating thaw history	James *et al.* (2024) [20]

3.2 Critical control points (CCPs) in cold chain

Table 2: Represents critical control points from harvest to consumer

CCP stage	Failure risk	Consequence	Best practice	References
On board preservation	Delayed chilling (>2 hrs)	3-log increase in Pseudomonas spp.; Advanced rigor mortis	Real-time temperature alerts; Automated ice dosing	Wang *et al.* (2024); Huss (1995) [61]
Freezing rate	Slow freezing (>2 hrs from 0°C to -5°C)	Drip loss increases 8-12%; Texture degradation	IQF/Cryogenic freezing; High-pressure shift freezing	Zhu *et al.* (2023) [70]; Sampels (2023) [45]
Storage stability	Temperature fluctuations >3°C	TBARS increases 0.5-2.0 mg MDA/kg; Recrystallization	AI-optimized warehouses; PCM buffers	Karoui *et al.* (2024); Liu *et al.* (2023) [21, 27]
Transport integrity	Door openings (>3 mins); Power failure	Localized warming to -10°C; Listeria reactivation	Solar-powered backup; Geofenced door-lock systems	Zhang *et al.* (2024) [67]
Retail display	Glass-door cabinets; Frequent lid openings	Surface temp. increases to -12°C; Shelf-life decreases 30%	Closed cabinets with anti-fog coatings; Night blinds	Badia-Melis *et al.* (2023) [4]

4. Recent advances in fish freezing technologies

4.1 Pressure-Assisted Processing

Pressure-Assisted Processing (PAP) serves as a non-thermal method of preserving food, which has attracted significant attention over the past few years due to its ability to maintain the taste, texture and nutritional value of food items (Chen, 2022; Khouryieh, 2021; Valø *et al*., 2020) [63, 22]. The mechanism of Pressure-Assisted Processing (PAP) entails exposing food items to elevated water-based pressure, generally between 100 and 800 MPa, over a specific time period. (Khouryieh, 2021) [22]. The applied pressure in PAP is evenly and rapidly distributed across the whole food item, irrespective of its size, shape, or composition, providing a prominent benefit over traditional heat-based processing techniques. In the seafood industry, one of the primary applications of PAP is microbial inactivation. Studies have demonstrated that PAP effectively reduces the presence of microorganisms in seafood products, including harmful bacteria such as *Listeria monocytogenes* and *Vibrio parahaemolyticus*, both of which play a significant role in causing food-borne illnesses linked to seafood (Roobab *et al*., 2022) [42]. The use of high pressure damages the cellular structures of microorganisms and leads to the inactivation of a wide range of microbes, including bacteria, yeasts and molds, thereby improving microbial safety and prolonging the shelf life of seafood products (Khouryieh, 2021; Roobab *et al*., 2022) [22, 42]. Specifically, applying high pressure damages the microbial cell membranes and blocks essential enzyme activities, effectively stopping microbial growth and reproduction (Roobab *et al.*, 2022) [42].

4.2 Ultrasonic waves

Ultrasonic waves is a developing non-thermal food processing technique that has attracted significant attention in recent years for its ability to enhance food safety and quality while preserving nutritional content and sensory attributes (Ma *et al*., 2023; Sireesha *et al.*, 2022) [28, 48]. This technique utilizes high-frequency sound waves, usually between 20 kHz and 1 MHz, to generate mechanical effects like cavitation within the food structure. These effects can damage microbial cells and enzymes, resulting in their inactivation (Ma *et al.*, 2023; Sireesha *et al.*, 2022) [28, 48]. The strength of ultrasound treatment can be accurately adjusted to maximize the inactivation of specific microorganisms and enzymes, allowing for tailored processing conditions (Hasan *et al.*, 2023; Ma *et al*., 2023) [28, 16]. Ultrasonication has demonstrated improvements in physicochemical properties, including texture, color and water-holding capacity (WHC). Moreover, it has been shown to increase omega-3 fatty acid content while mitigating lipid oxidation (Sireesha *et al.*, 2022) [48]. In terms of microbial safety, ultrasonication effectively reduces bacterial and viral loads in seafood products (Ma *et al.*, 2023) [28]. For instance, Ma *et al*. (2023) [28] explored the use of ultrasound for the inactivation of *Vibrio parahaemolyticus* in raw oysters, reporting a 3.13 log CFU/g reduction after treatment with 7.5 W/mL ultrasound for 12.5 minutes. Additionally, the ultrasound treatment delayed microbial proliferation and quality deterioration during cold storage, better preserving the oysters color, texture and flavor compared to conventional heat treatments (Ma *et al*., 2023) [28].

4.3 Electric Pulse Processing

Electric Pulse Processing (EPP) technology is a novel food processing method that utilizes short bursts of high-voltage electric fields, typically ranging from 20 to 80 kV/cm, to permeabilize microbial cell membranes, resulting in their inactivation (Abel *et al.*, 2022; Khouryieh, 2021; Pérez-Won *et al*., 2021) [1, 22, 35]. Similar to ultrasound technology, the effectiveness of EPP treatment can be fine-tuned by adjusting the electric field intensity, pulse duration and the number of pulses to target specific microorganisms. Notably, EPP has been demonstrated to effectively inactivate *Listeria monocytogenes* in vacuum-sealed cold-smoked salmon thereby extending the product's shelf life (Aymerich *et al*., 2019) [3]. Additionally, Pérez-Won *et al*. (2021) [35] investigated the combined effects of Electric Pulse Processing (EPP), Carbon Dioxide (CO_2) and Pressure-Assisted Processing (PAP) on the physicochemical characteristics and microbial shelf life of coho salmon stored under refrigerated conditions, both before and after rigor mortis. Their findings revealed that the combined treatments more effectively mitigated color differences in pre-rigor salmon relative to post-rigor samples (Pérez-Won *et al*., 2021) [35].

EPP technology presents promising applications within the seafood industry. Notably, it has been shown to improve the extraction of bio-active compounds from seafood byproducts adds value to these often underused resources (Franco *et al.*, 2020) [14]. However, despite the potential benefits of EPP, there are several challenges that must be overcome. For example, a major drawback is the high cost of the technology, which may hinder its broad implementation in the seafood sector (Khouryieh, 2021) [22]. Moreover, EPP treatment may cause lipid oxidation, which can produce unpleasant off-flavors in seafood products (Shiekh *et al*., 2021) [47].

5. Innovations in cold chain logistics

5.1 Internet of things (IoT) and Digitalization in cold supply chain

Fish is a highly perishable product that requires specialized management throughout the distribution process to maintain its quality and freshness. Central to this management is maintaining a low temperature, typically between 1-4°C, which helps preserve the fish's freshness until it reaches consumers. The rising demand and production of fish have prompted governments and sellers to develop and enhance cold supply chain distribution networks. As highlighted by Rumape *et al*. (2022) [43], cold chain systems are essential across various industries, particularly in food processing, where they play a critical role in preserving product quality. For fishery products, cold storage is indispensable for optimizing temperature control and ensuring freshness retention. Time and temperature are key factors in effective cold chain management (Hanafiah *et al.*, 2024) [15] and optimization is increasingly achieved through real-time temperature monitoring of frozen fish (Zhan *et al*., 2018) [65]. This real-time data serves as a basis for determining the energy requirements necessary for maintaining the ideal temperature and environmental conditions to safeguard product quality. Sensors are widely employed to monitor both product and ambient temperatures, providing critical data to prevent spoilage (Tavares *et al*., 2021) [53]. Advancements in sensor technology have extended their capabilities to measure humidity, moisture content and freshness indicators in fish products. These sensors typically include integrated transmitters and power sources to facilitate seamless data transmission. Communication networks then connect the various components of the supply chain, enabling efficient data exchange. One of the most promising technologies in this domain is the Internet of Things (IoT), which offers flexible and long-term connectivity solutions. IoT compatibility with cold chain networks ensures widespread and reliable data communication, supported by the ongoing expansion of internet infrastructure globally (Rakesh *et al.*, 2019) [38].

5.2 A Case study of PT Agro Boga Utama to use LOCUS system

LOCUS: An Intelligent System Transforming Logistics Operations through Digitalization. PT Agro Boga Utama, a distributor and manufacturer specializing in high-quality halal frozen seafood products, sought an efficient and intelligent solution to digitize and optimize its logistics operations. Prior to implementing LOCUS, the company's operations team faced significant challenges in delivery planning, which was conducted manually and lacked visibility into truck movements and delivery statuses once shipments left the warehouse. This manual process was time-consuming, resulting in delays in order picking and delivery (Hanafiah *et al*., 2024) [15].

With the adoption of LOCUS, PT Agro Boga Utama successfully automated its delivery planning and established a fully trackable delivery system to manage its fleet of refrigerated trucks. This innovation ensured the integrity of products was preserved regardless of the distance traveled or duration of transit. LOCUS integrates GPS tracking via an interactive dashboard and mobile applications, providing real-time updates on delivery status and actual transit times (Tobing, B 2015) [54].

Key components of the LOCUS platform, DispatchIQ and TrackIQ, utilize a proprietary geocoding engine and machine learning algorithms to enable efficient route planning and optimal scheduling of orders. Serving as a comprehensive Transport Management System (TMS), LOCUS supports the company in managing customers, drivers, locations and sellers, while streamlining the entire supply chain (Tobing, B 2015) [54]. This digital transformation has markedly improved operational efficiency and delivery reliability for PT Agro Boga Utama.

5.3 Digitization via the app

Drivers utilize the LOTR mobile application to record shipment statuses, with delivery updates provided in real-time through the app. The system generates Electronic Proof of Delivery (ePOD), which includes photographs, digital signatures and documented reasons for cancellations or partial deliveries, thereby enhancing transparency and visibility throughout the delivery process (Raut *et al*., 2015) [40].

6. Quality assurance and freshness assessment

6.1 Advanced sensor technologies for freshness assessment

6.1.1 Biosensors

The assessment of aquatic product freshness using biosensor devices has advanced rapidly in recent years (Sriramulu *et al*., 2024) [50]. Biosensors operate by detecting chemical or biological indicators via the targeted recognition of biological elements like enzymes, antibodies, or DNA, enabling highly direct and specific detection. Consequently, biosensors offer superior sensitivity and specificity compared to conventional electronic nose and tongue techniques. Moreover, biosensors can rapidly identify key freshness Indicators in seafood products, including histamine and hypoxanthine, which are critical indicators of spoilage. Unlike conventional electronic noses and tongues, biosensors generally comprise three core components: biorecognition elements, transducers, and signal processing systems. The biorecognition elements such as enzymes, antibodies, nucleic acids, or whole cells specifically interact with the target analytes, initiating the detection process. After the biorecognition element specifically interacts with the target analyte, the transducer translates this biological interaction into a detectable physical signal, such as electrical, optical or thermal outputs. The signal processing system then enhances, analyzes and displays these signals in a readable format. In recent years, significant advancements have been achieved in using biosensors to evaluate the freshness of aquatic products.

For instance, Wang *et al*. (2021) [58] developed an electrochemical biosensor utilizing a copper-based Metal-Organic Framework (MOF) nanofiber membrane, designed to immobilize xanthine oxidase for the detection of hypoxanthine and xanthine in chilled seafood. Liu *et al*. (2020) [26] introduced a non-reversible sensor designed to detect protein food deterioration, in foods such as seafood and meat, addressing the demand for reliable monitoring of food quality decline during storage. This sensor can aid food processors in preventing deception concerning product quality, thus improving food safety.

Additionally, Milintha Mary *et al*. (2023) [30] introduced a dual sensor that uses a pH indicator to assess the freshness of packaged seafood by tracking color shifts, offering an efficient method for evaluating quality. Franceschelli *et al*. (2021) [13] highlighted that biosensors for detecting fish freshness address the drawbacks of traditional methods by providing non-invasive, non-destructive monitoring that allows for real-time process control, without requiring complicated sample preparation. Their sensor employs conductive polymer components coupled with specialized electronics to identify subtle variations in signals, allowing freshness evaluation without depending on microbial counts.

Electrochemical biosensors especially have shown considerable benefits in accurately detecting and screening contaminants in food, playing a crucial role in maintaining seafood freshness (Majer Baranyi *et al*., 2023) [29]. The widespread adoption of biosensors in aquatic product has several key factors contribute to the evaluation of freshness: (1) their high sensitivity and accuracy stemming from specific molecular recognition; (2) their rapid detection capabilities and portability, as many biosensors are designed for real-time, on-site monitoring and (3) the simplicity of data interpretation, since biosensors target specific analytes, avoiding the need for complex pattern recognition algorithms used in electronic noses and tongues. This maked biosensors more clear in both functioning and outcome evaluation. Facilitating timely freshness monitoring and quality control (Majer Baranyi *et al*., 2023) [29].

6.1.2 Flexible Sensors

The increasing significance of cold chain logistics within the aquatic product supply chain has sparked considerable research into using flexible sensors for freshness evaluation, due to their high sensitivity, superior attach ability and portability (Huang *et al*., 2023; Li *et al*., 2022) [17, 25]. Typically, flexible sensors consist of flexible substrates, conductive materials, and sensitive layers. Substrate materials such as polyimide (PI) and polydimethylsiloxane (PDMS) provide the sensors with remarkable flexibility and durability. Conductive materials, including silver nanowires and carbon nanotubes, ensure reliable electrical signal transmission. The sensitive layer determines the sensor's detection performance by enhancing responsiveness to specific gases or chemical substances through functionalization (Li *et al*., 2022) [25].

A color-based sensor that detects amine substances produced during fish deterioration inside packaging, allowing continuous freshness tracking through visible color variations (Pacquit *et al.*, 2004) [34]. A tagging system that combines flexible sensors with wireless radio frequency communication technology to enable real-time monitoring of food quality by detecting volatile amine compounds in aquatic product samples (Andre *et al*., 2024) [2]. Permanent wireless pH sensor was designed for identifying spoilage in packaged meat products, showing promise for use in aquatic product freshness monitoring. A hydrogel composed of polyvinyl alcohol and chitosan, allowing visible, real-time observation of freshness by responding to Total Volatile Basic Nitrogen (TVB-N) and pH level changes (Zeng *et al*., 2024) [64]. Furthermore, the effectiveness of flexible sensors used for assessing shrimp freshness, confirming their effectiveness in determining the freshness of aquatic products (Zhu *et al*., 2023) [70].

6.2 Biomimetic Sensors

6.2.1 Artificial taste sensor

Over the past few years, progress in sensor innovations have resulted in the creation of development of diverse sensing instruments based on various product freshness assessment criteria, offering innovative approaches to ensure quality management within refrigerated supply chains. Among these, electronic tongues and electronic noses are the most commonly applied devices designed to mimic human gustatory and olfactory senses respectively. These technologies integrate multiple physicochemical sensing methods in order to provide multidimensional monitoring of seafood product quality. In parallel biosensors which primarily rely on microbial detection mechanisms, have enhanced the accuracy of freshness evaluation. The adoption of these technologies has significantly improved the precision and effectiveness in identifying freshness thereby providing a scientific foundation for comprehensive cold chain logistics surveillance. Moreover, continuous innovation in flexible substances and manufacturing methods techniques has propelled the emergence of flexible sensors as a promising advancement in evaluating product freshness. The combination of such advanced sensing technologies offers substantial assistance in the ensuring the quality of seafood throughout the refrigerated supply chain. Artificial taste sensor technology employs arrays of chemical detectors in order to emulate biological gustatory mechanism, facilitating the detection and analysis of chemical constituents in liquid samples to assess the freshness of seafood items (Wei *et al*., 2024; Huang *et al*., 2023; Xiong *et al*., 2023) [60, 17, 62]. Its application for tracking the quality, safety, and storage duration of meat and seafood has demonstrated excellent performance for quick sensory profiling and product evaluation (Munekata *et al*., 2023) [31]. Furthermore, strong correlations between artificial taste sensor outputs and Biological sensory information have been established, underscoring its efficacy as a sensory evaluation and quality control tool (Cho *et al.*, 2022) [6]. The role of artificial taste sensor system in food safety and freshness assessment has been emphasized in several studies, highlighting their significance in aquatic product evaluation (Nowshad *et al.*, 2021) [33]. Additionally, Waimin *et al*. (2022) [56] developed a low-cost wireless pH sensor technology aimed at assessing microbial spoilage risks in aquatic products, showing considerable potential for application across the supply chain. Successfully applied artificial taste sensor technology combined with sensory assessment and pattern analysis techniques including techniques like Principal Component Analysis (PCA) and Hierarchical Clustering Analysis (HCA) to detect counterfeit green tea, achieving promising results. Piccinin *et al.* (2024) [36] further demonstrated the capacity of artificial taste sensors to quantify lactose content in commercial foods, indicating broad applicability in the analysis of food quality. In fishery products, (Duan *et al.*, 2022) [9-10] highlighted the effectiveness of Engineered Nano Materials (ENMs) as freshness assessment tools. However, they also noted the potential risks associated with nanomaterial use in food applications, calling for careful consideration of safety issues.

6.2.2 Artificial olfaction system

The artificial olfaction system comprises a collection comprising gas sensors intended for the detection of Volatile Organic Compounds (VOCs) emitted by aquatic products. The sensors produce unique electrical responses to the VOCs, which are then analyzed by pattern recognition systems employing techniques such as Artificial Neural Networks (ANN) Principal Component Analysis (PCA) and Support Vector Machines (SVM) to accurately assess the quality status of the products (Duan *et al.*, 2022) [9-10]. The operational mechanism of the artificial olfaction system consists of three main stages. First, a sensor configuration typically comprising materials such as metal oxide-based materials, polymeric conductors, or quartz crystal resonators engages with the VOCs emitted by seafood items. Every sensor generates a characteristic signal that collectively creates a specific "signature" representing the odor profile. In the final step, this sensor response information is analyzed through computational models to detect and categorize the odors, thereby enabling effective freshness evaluation ((Nowshad *et al.*, 2021) [33].

An artificial olfaction -based system to assess the freshness of tilapia, utilizing the normalized absolute data approach and attaining an accuracy rate of 93.88% (Radi *et al*., 2021) [37]. With continuous technological advancements, the ability of artificial olfaction system to classify and predict has markedly advanced. For instance, constructed a predictive system using discriminant neural network evaluation combined with the partial least squares approach to differentiate fish quality and estimate microbial indicators, achieving an accuracy of 85%. To address contemporary food preservation needs, artificial olfaction system is increasingly combined with the IoT (Internet of Things). A compact artificial olfactory device built upon IoT framework enabling immediate freshness evaluation of foods stored in refrigerators, demonstrating strong capability for distinguishing unspoiled, moderately fresh, and deteriorated seafood items (Wang *et al.*, 2018) [65]. Similarly, Wijaya *et al*. (2023) [61] combined artificial olfaction technology utilizing machine learning models to develop a rapid, cost-effective and precise method for identification of seafood quality, achieving excellent classification accuracy. Recent applications of electronic noses also include monitoring variations in aroma-related compounds within processed food products. These technological advances have greatly enhanced the sensitivity and precision of spoilage detection and freshness assessment across diverse seafood products (Wang *et al*., 2018) [65]. The combination of IoT technology and machine learning techniques further enables instant tracking and accurate categorization, making artificial olfaction systems more versatile and efficient. However, challenges remain, notably the susceptibility of gas sensor arrays to environmental factors such as temperature fluctuations, humidity variations and interference from other volatile compounds, which can affect device accuracy (Nowshad *et al*., 2021) [33].

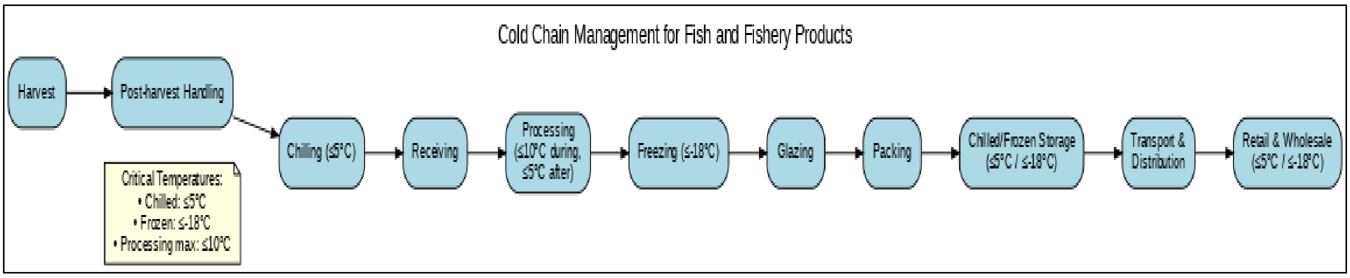
While both artificial olfaction systems and artificial taste sensors emulate biological sensory systems for identifying and evaluating the freshness of seafood, they differ in their sensing principles (Duan *et al.*, 2022) [9-10]. Artificial taste sensors primarily mimic the biological gustatory system, concentrating on the assessment of flavour-related chemical compounds present in fluid samples. In contrast, olfaction systems replicate the biological smell system, detecting aromatic organic molecules present in gaseous specimens. Both technologies to classify that are able to be examined through pattern identification and statistical methods for categorizing and predict the quality of complex aquatic products (Wang *et al*., 2018) [65]. However, electronic tongue systems tend to be more complex due to the larger volume of sensory input along with additional data handling procedures, thereby consequently raise implementation expenses. Moreover, the response time of electronic tongues is generally slower because of the need for fluid management and sequential sensing detection procedures, resulting in longer overall detection times (Cho *et al*., 2022) [6].

Table 3: Represents comparison of advanced sensor technologies

Advanced sensor technologies	Advantages	Disadvantages	Application
Bio-Sensors	Highly accurate at correctly identifying both positive and negative cases	Low stability, making it unsuitable for accurate biochemical analysis	Precise biochemical analysis under controlled environments.
Flexible sensors	Adaptable, versatile in function, and ideal for real-time and continuous tracking	Currently encountering difficulties with stability and prolonged use in complex conditions.	Instant freshness detection and ongoing monitoring of seafood products
E-Tongue	Detects low levels of substances produced in the initial stages	Easily affected by environmental factors and involves high equipment expenses.	Quick identification of flavor in food
E-Nose	Quick response, rapid monitoring, minimal preparation, broad detection range, and high consistency	Prone to environmental disturbances and requires costly equipment.	Fast identification of odors in food products

7. Regulatory Guidelines

According to the Codex Alimentarius Commission (2014) [7], the cold chain refers to a continuous system of methods used to consistently maintain proper food temperatures throughout all stages from receiving and processing to transportation, storage and retail. Within the fishing industry, effective cold chain management is crucial throughout the entire supply chain to maintain product quality, safety and marketability from aquaculture or wild capture through post-harvest handling, processing, packaging, transportation and final retail distribution., maintaining an unbroken cold chain is essential for preserving the freshness and safety of fish and seafood products. Conventional preservation methods such as the application of ice, utilization of refrigerated seawater, storage in cold facilities, and chilling or freezing are widely adopted to ensure the maintenance of optimal low-temperature conditions. However, these temperature controls should be complemented by proper hygienic handling procedures to effectively slow down spoilage and prevent contamination (Sutariya *et al*., 2021) [52]. The Codex guidelines emphasize the critical role of time and temperature controls across every phase of the cold chain, encompassing post-harvest handling, chilling, receiving, processing, freezing, glazing, packaging, cold storage, transportation, distribution, retail and wholesale. These Guidelines act as a complementive resource for best practices aiming to ensure the safety, quality and wholesomeness of raw and minimally processed fish and fishery products preserved through chilling and freezing techniques.



Flowchart 1: Cold chain management from production to marketing of fish and fishery products

8. SWOT Analysis

Conducting a SWOT analysis on emerging technologies for seafood processing offers valuable insights for researchers, industry stakeholders, and policymakers focused on advancing these innovations. This analytical framework highlights that emerging technologies possess significant strengths compared to conventional techniques, especially in maintaining product quality and guaranteeing food safety. Notably, these technologies contribute to extended shelf life, superior preservation of nutritional and sensory attributes, improved food safety and enhanced energy-saving (Laorenza *et al*., 2022) [23]. Such advancements are pivotal in addressing the increasing consumer demand for seafood products that are high-quality, safe and sustainably produced. Furthermore, emerging technologies improve sensory characteristics such as taste and texture, thereby increasing overall consumer acceptability beyond what traditional processing methods typically achieve. As a strategic planning tool, SWOT analysis enables a comprehensive evaluation of the advantages, disadvantages, potential opportunities and risks related to these technologies. The capability of Evolving processing methods to maintain the nutritional and organoleptic qualities of seafood effectively tackles one of the seafood industry's critical challenges.

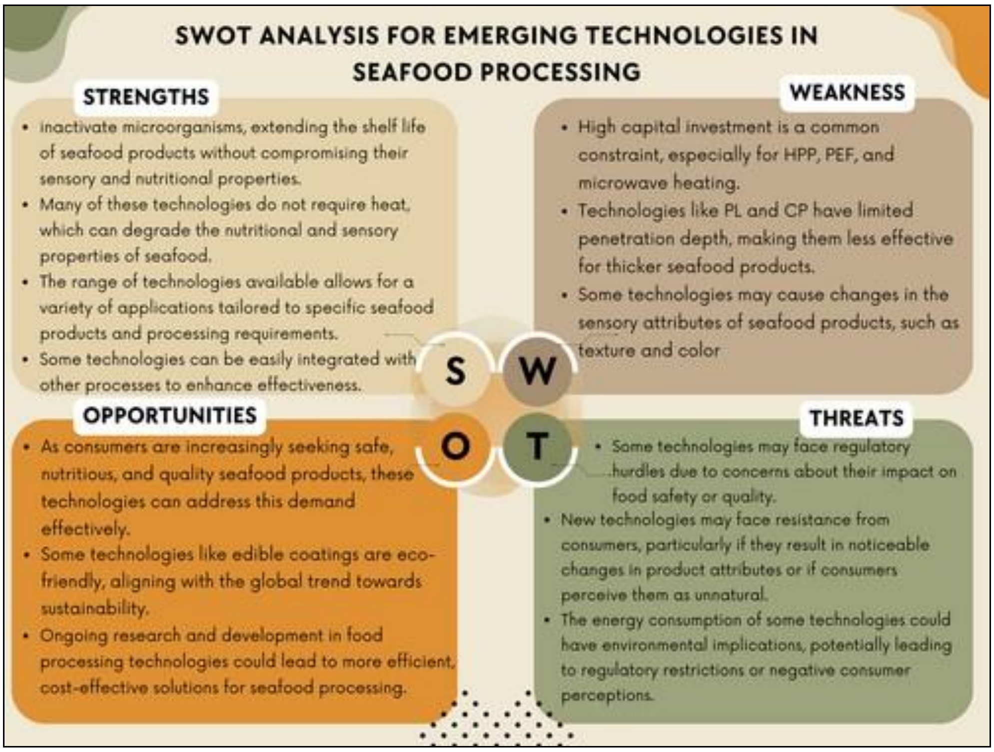


Fig 1: SWOT analysis for emerging technologies in seafood processing

9. Challenges and Future Directions

Although some technologies require substantial initial investments and the adoption of advanced freezing and cold chain technologies in seafood processing encounters several significant challenges. Technical barriers include the high energy consumption associated with ultra-low-temperature freezers, inadequate infrastructure in remote fishing communities and the incompatibility of some equipment with renewable energy sources (Nowshad *et al.*, 2021) [33]. Environmentally, the continued reliance on synthetic refrigerants such as HydroFluoroCarbons (HFCs) and diesel-powered transportation contributes substantially to greenhouse gas emissions, with cold chains accounting for approximately 4-6% of global CO_2 emissions. Despite these challenges, the increasing consumer preference for seafood products that are high-quality, safe and easy to use underscores the critical role these emerging technologies will play in the industry's future. Amid increasing environmental concerns, the seafood sector must prioritize the long-term viability of these technologies by advancing Low-energy and water-conserving methods, which are expected to drive ongoing innovation (Laorenza *et al.*, 2022) [23]. Moreover, the successful implementation of these techniques ensuring safety, quality assurance and sustainability will be essential in increasing consumer trust. Cost-efficiency also remains a decisive factor in their widespread adoptionefits in terms of enhanced product quality, improved safety measures and prolonged shelf life justify these costs (Khouryieh, 2021) [22]. Future research directions should prioritize on improving the efficiency and cost-effectiveness of these technologies, exploring synergistic applications, and assessing their effects across various seafood species and products. Additionally, consumer education and transparent communication regarding the advantages of these technologies will be crucial for market acceptance.

10. Conclusion

As mentioned, fish is a highly perishable food with a limited shelf life. Freezing and cold chain management it is likely one of the most commonly employed techniques for preserving fish. In this review, the advancements in fish freezing and cold chain management underscore a critical shift toward integrated technological and sustainable solutions, yet significant barriers impede universal adoption. Persistent technical limitations such as energy-intensive freezing processes, infrastructure gaps in developing regions and scalability challenges of automation intersect with economic constraints like high capital costs and labor shortages. Environmental concerns, particularly refrigerant emissions and waste valorization inefficiencies, further complicate progress. However, these challenges delineate clear pathways for innovation: prioritizing renewable energy integration (e.g., solar-thermal hybrid systems), AI-driven predictive logistics and circular economy models for waste-to-value conversion. Future success hinges on collaborative frameworks spanning policy incentives, public-private partnerships, and standardized "green cold chain" certifications to democratize access, enhance climate resilience, and reduce post-harvest losses by 30-50%. By harmonizing cutting-edge freezing technologies with eco-efficient logistics, the sector can transform from a carbon-intensive chain into a transparent, equitable and adaptive global system, ensuring seafood security while advancing planetary health.

Conflict of Interest
Not available

Financial Support
Not available

11. References

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