Review Article

Review on Fish Production Enhancement and Preservation Technologies

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Abstract | Fish and fishery products are highly valued food commodities due to their exceptional nutritional profile, including high-quality protein, essential vitamins, minerals, and beneficial unsaturated fatty acids. However, seafood is highly perishable, necessitating proper processing to maintain its quality, freshness, and safety. Modern consumers demand minimally processed fishery products that retain their natural attributes without compromising nutritional integrity. Consequently, innovative technologies in aquaculture and seafood processing have become essential for sustaining industry growth while ensuring food safety. Advancements in aquaculture, such as biofloc technology, robotic systems, sensor-based monitoring, and nano-vaccinology, have significantly improved fish farming productivity and strengthened the economic stability of fish farmers. However, freshly harvested fish undergo rapid biochemical changes, including rigor mortis, oxidative spoilage, autolysis, and microbial degradation. These processes lead to the breakdown of various compounds, causing undesirable changes in odor, flavor, and texture, thereby reducing seafood quality and shelf life. To mitigate spoilage and extend shelf life, novel food processing technologies are being explored. These include high hydrostatic pressure (HHP), seafood irradiation, pulsed light technology, pulsed electric fields (PEF), and microwave processing. These emerging techniques offer promising solutions for seafood preservation while maintaining nutritional quality, texture, and flavor. Importantly, they align with current consumer preferences for fresh, additive-free, and minimally processed food products. As health-conscious consumers increasingly prioritize food safety and nutritional value, adopting innovative seafood processing technologies is critical to meeting market demands. These advanced preservation methods ensure that seafood products remain safe, nutritious, and of high quality, with minimal processing intervention. By integrating cutting-edge aquaculture and food preservation techniques, the seafood industry can achieve sustainability, enhance productivity, and deliver high-value products that cater to evolving consumer preferences.

Editor | Muhammad Abubakar, National Veterinary Laboratories, Park Road, Islamabad, Pakistan.
Received | January 15, 2025; **Accepted** | February 19, 2025; **Published** | February 26, 2025
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Citation | Getahun, A., Y. Kechero and N. Yemane. 2025. Review on fish production enhancement and preservation technologies. *Veterinary Sciences: Research and Reviews*, 11(1): 54-70.
DOI | https://dx.doi.org/10.17582/journal.vsrr/2025/11.1.54.70
Keywords | Fishery products, Aquaculture technology, Seafood processing, Food preservation, Food safety, Minimally processed foods

Introduction

The global population continues to rise at an unprecedented rate, leading to a substantial increase in the demand for food. In today's world, there is a growing awareness of the importance of consuming nutritious food, with fish ranking among the most sought-after foodstuffs due to its high nutritional value. Aquaculture, which has been practiced for centuries, plays a crucial role in providing high-quality protein to human populations (Gui *et al*., 2018). The Food and Agriculture Organization (FAO) reported that global seafood consumption surged from 9.9 kg per capita in the 1960s to 20 kg in 2016. Notably, aquaculture production has outpaced wild fisheries since 2013 (FAO, 2020). Additionally, fishery product exports from developing nations generated an income of $80 billion, contributing to an estimated $148 billion in global seafood exports in 2014. Compared to other agricultural sectors, aquaculture demonstrates greater diversity in terms of species, feed, production systems, diseases, products, business structures, and marketing strategies (FAO, 2020). Over the last five decades, advancements in scientific research and technology have significantly contributed to the rapid expansion of the aquaculture industry (Burnell and Allan, 2009).

The biochemical composition of live fish varies between species and even within the same species due to factors such as diet, migratory activity, and reproductive changes. Despite these differences, fish remain one of the most nutritious food sources, providing approximately 20% of the protein intake for one-third of the world's population (Béné *et al*., 2007). Furthermore, fish serve as an excellent source of omega-3 (ω-3) polyunsaturated fatty acids (PUFAs), which are known for their numerous health benefits. In addition to essential fatty acids, fish contain high levels of micronutrients such as vitamin D and various minerals, often found in greater concentrations in aquatic animals than in land-based meats and plants (Mohanty *et al*., 2017).

Technological advancements have revolutionized nearly every aspect of aquaculture, enhancing productivity and efficiency. Many emerging technologies have significantly improved aquaculture production. Traditional labor-intensive farming methods have transitioned to mechanize and, more recently, automated systems. While labor-intensive models rely on human expertise and are associated with high labor costs, automated systems necessitate skilled workers, affecting cost-effectiveness. Additionally, resources such as water and feed remain critical concerns. As labor shortages persist and demand for aquaculture products rises, there is an urgent need for intelligent aquaculture models. Innovations such as Biofloc Technology, Nanovaccinology, Sensor Technology, and Robotics for Sustainable Fish Farming have paved the way for intelligent aquaculture. Advanced disease management technologies (Kelly and Renukdas, 2020) have also contributed to reducing disease prevalence in aquaculture systems. Despite these advancements, challenges remain, particularly in meeting the increasing demand for seafood as the global population expands (FAO, 2020). The industry must enhance aquaculture production while addressing environmental degradation, declining fish meal and oil supplies, and climate change, all of which pose significant threats to seafood production (Abdelrahman *et al*., 2017; Li *et al*., 2011; Shen *et al*., 2020).

The future of aquaculture depends on its ability to develop sustainably and profitably (FAO, 2020). Emerging technologies continue to be integrated into the industry, offering innovative solutions for enhancing seafood production. Disruptive technologies such as biofloc technology, robotics, sensor technology, blockchain, and nanovaccinology are transforming aquaculture. Additionally, advanced food processing technologies, including high hydrostatic pressure, seafood irradiation, pulsed light, and microwave processing, are being employed to improve seafood preservation. These reviews highlight recent technological advancements that contribute to the enhancement and preservation of fish products, ensuring a sustainable and productive future for the aquaculture industry.

Benefit of preservation and processing of fish products

Fish is a highly perishable food that begins to spoil as soon as it is caught, perhaps even before it is taken out of the water (Tsironi *et al*., 2020). Therefore, particular care is required during harvesting and throughout the supply chain to preserve its nutritional attributes, avoid contamination, reduce loss and waste, and deliver a high-quality product (Peñarubia, 2021).

Since fish farms and other capturing sites are often located far from the marketplace, there is a risk of decomposition and uncertainty in sales. When fish is caught in quantities exceeding immediate consumption, preservation becomes essential for future use. Effective preservation and processing ensure that fish remains fresh for an extended period with minimal loss of flavor, taste, odor, nutritive value, and digestibility (Ugochukwu, 2017).

Processing is crucial in reducing food loss and waste, thereby lessening pressure on fishery resources and enhancing the sustainability of the sector. However, processing generates substantial by-products, including heads, bones, guts, and shells, which make up 30–70% of the whole fish. These often go unutilized, turning into waste (Amit *et al*., 2017). Various methods can transform these by-products into value-added products, such as animal feed (fishmeal, fish oil), biofuel, pharmaceuticals (omega-3 oils), fish leather, silage, and fertilizers (Coppola *et al*., 2021).

Fish production enhancement technology

Biofloc technology for sustainable fish farming: Biofloc Technology (BFT) has emerged as an innovative and sustainable strategy in aquaculture, transforming harmful nitrogenous wastes into valuable microbial biomass that serves as a natural feed source. Developed to optimize environmental control in aquatic animal production, Biofloc Technology (BFT) addresses critical challenges such as high feed costs (which account for 60% of total expenses) and limitations posed by water and land availability. By enabling high stocking densities and reducing the need for water exchange, Biofloc Technology (BFT) is particularly advantageous for intensive fish farming systems (Khanjani *et al*., 2020).

The fundamental concept behind biofloc technology lies in the creation of a nitrogen cycle by maintaining a high carbon-to-nitrogen (C/N) ratio. This stimulates the growth of heterotrophic microbes that assimilate nitrogenous waste, converting it into a useful feed source for cultured species (Ray and Mohanty, 2020). In biofloc systems, heterotrophic bacteria dominate the microbial community and form the biofloc structure, while chemoautotrophic nitrifiers exist in smaller quantities, thereby reducing nitrogen release into the pond ecosystem. Additionally, Actinobacteria contribute to biofloc formation and may offer protective benefits against fish pathogens, though they can also cause undesirable off-flavors in fish flesh and water (Liu *et al*., 2019).

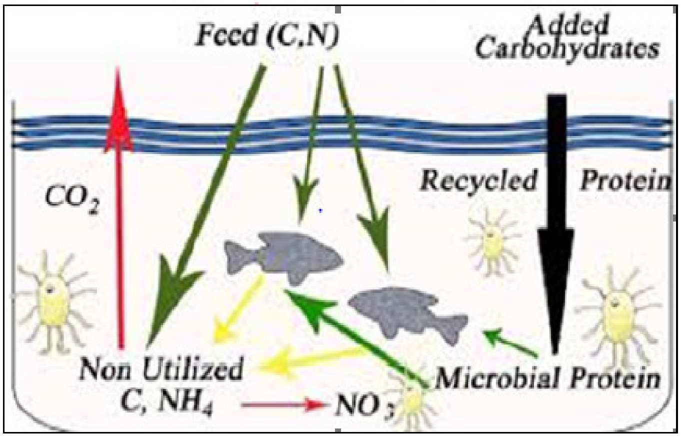

Figure 1: *Biofloc Technology Model (Sources: Ray and Mohanty, 2020).*

Nitrifying bacteria play a vital role in ammonia conversion within biofloc systems. Ammonia oxidizers first transform ammonia into nitrite, which is subsequently converted into nitrate by nitrite oxidizers (Chen *et al*., 2019). However, excessive nitrite and nitrate levels can be harmful to aquatic animals, negatively impacting gill tissues, causing respiratory problems, and increasing mortality rates (Kuhn *et al*., 2010b). Therefore, continuous monitoring of environmental parameters such as temperature, salinity, alkalinity, pH, dissolved oxygen, settling solids, total suspended solids, and orthophosphate is essential for system stability (Emerenciano *et al*., 2017). The improvement in water quality in BFT systems arises from complex interactions among these parameters, underscoring the importance of further research to enhance aquaculture production methods (Jamal *et al*., 2020).

Biofloc technology offers multiple advantages over traditional fish farming methods. It is an eco-friendly approach that eliminates the need for wastewater drainage after culture, reduces environmental impact, optimizes land and water usage, and generates protein-rich biofloc as supplementary feed (Reddy, 2019). Moreover, Biofloc Technology (BFT) enhances biosecurity by reducing wastewater pollution and lowering disease risks (Arias-Moscoso *et al*., 2018). By improving survival rates, growth performance, and feed conversion efficiency, BFT serves as a cost-effective alternative that decreases reliance on wild fisheries for fishmeal production (Reddy, 2019).

Biofloc Technology (BFT) is an advanced aquaculture system that minimizes water exchange by using a recirculating setup with internal waste treatment (Liu *et al*., 2019). In contrast, traditional aquaculture requires frequent water exchange, leading to high water consumption and environmental pollution (Reddy, 2019). Biofloc Technology (BFT) reduces feed costs by utilizing microbial protein as a supplementary feed source, making it more cost-effective (Bossier and Ekasari, 2017). Traditional methods rely heavily on formulated feed, increasing operational expenses (Reddy, 2019). Moreover, Biofloc Technology (BFT) maintains superior water quality by assimilating toxic nitrogen compounds and stabilizing microbial ecosystems (Ray and Mohanty, 2020), whereas traditional methods experience water quality deterioration due to waste accumulation, requiring frequent exchanges or filtration (Emerenciano *et al*., 2017).

Biofloc Technology (BFT) supports higher stocking densities due to improved water quality and biosecurity (Avnimelech, 2015), whereas traditional methods require lower densities to avoid oxygen depletion and waste buildup (Hargreaves, 2013). Additionally, BFT reduces pathogen spread by minimizing water exchange and using beneficial microbes (Arias-Moscoso *et al*., 2018), while traditional systems pose a higher disease risk (Reddy, 2019). Environmentally, BFT is eco-friendly, minimizing pollution (Crab *et al*., 2012), whereas traditional systems contribute to eutrophication (Jamal *et al*., 2020). Although BFT has high initial costs, it is more sustainable long-term, whereas traditional methods face higher costs over time (Chen *et al*., 2019).

Robotic technology for sustainable fish farming: Aquaculture production is a complex process involving multiple labor-intensive and costly steps, such as feeding, cleaning ponds and nets, monitoring fish behavior, and removing sick fish (Lucas *et al*., 2019). These tasks can be challenging without the aid of machines. Additionally, due to the high diversity of aquaculture species and culture systems, few customized solutions exist that can work universally across the industry (Kruusmaa *et al*., 2020). However, technological advancements have introduced solutions to address these challenges. Robots have been applied to feeding, pond and net cleaning (Osaka *et al*., 2010), vaccine injection (Lee *et al*., 2013), and sick fish removal (Antonucci and Costa, 2020; Sun *et al*., 2020), reducing labor and operational risks. Robots are also utilized for fish health monitoring, escape prevention (Ohrem *et al*., 2020), and real-time behavior tracking (Kruusmaa *et al*., 2020).

Table 1: *Comparison of biofloc fish production technology with traditional methods.*

Feature	Biofloc technology (BFT)	Traditional aquaculture methods
Water usage	Minimal water exchange, recirculating system with internal waste treatment (Liu *et al*., 2019).	Requires frequent water exchange, leading to high water consumption and environmental pollution (Reddy, 2019).
Feed utilization and cost	Reduces feed costs by utilizing microbial protein as supplementary feed (Bossier and Ekasari, 2017).	High reliance on formulated feed, increasing operational costs (Reddy, 2019).
Water quality management	Maintains better water quality by assimilating toxic nitrogen compounds and stabilizing microbial ecosystems (Ray and Mohanty, 2020).	Water quality deteriorates due to waste accumulation, requiring external filtration or frequent water exchange (Emerenciano *et al*., 2017).
Stocking density	Supports higher stocking densities due to improved water quality and biosecurity (Avnimelech, 2015).	Lower stocking densities are required to prevent oxygen depletion and waste buildup (Hargreaves, 2013).
Disease control and biosecurity	Reduces pathogen spread by minimizing water exchange and utilizing beneficial microbes (Arias-Moscoso *et al*., 2018).	Higher risk of disease outbreaks due to direct exposure to external water sources (Reddy, 2019).
Environmental impact	Eco-friendly system with zero or minimal discharge, reducing pollution (Crab *et al*., 2012).	Causes nutrient pollution and eutrophication due to effluent discharge (Jamal *et al*., 2020).
Growth performance and survival rate	Enhances fish growth and survival rates by improving nutrient availability and feed conversion ratio (Reddy, 2019).	Growth rates depend on water quality and feed efficiency, often requiring more inputs (Kuhn *et al*., 2010b).
Operational cost and sustainability	Initial setup costs can be high, but long-term sustainability and cost-effectiveness are superior (Avnimelech, 2015).	Lower initial investment but higher long-term costs due to water exchange, feed dependency, and disease outbreaks (Chen *et al*., 2019).

Their ability to operate continuously under harsh conditions without human assistance enhances profitability in aquaculture. Many research institutes and companies, including Robotfish, Cermaq, Innovasea, SINTEF, SeaVax, Sublue, and the Massachusetts Institute of Technology, have developed or are developing robotic solutions. Some of these technologies have already been tested and proven effective (Ohrem *et al.*, 2020).

Robotic technologies have the potential to revolutionize sustainable fish farming by improving efficiency, reducing environmental impact, and optimizing resource use. However, their widespread adoption faces several limitations, particularly for small-scale farmers. One major barrier is the high upfront investment required for automated feeding systems, underwater drones, and AI-driven water quality sensors. These technologies are often more accessible to large-scale aquaculture businesses than to small or family-run farms due to their high costs (Dauda *et al.*, 2019). Additionally, the expenses related to maintenance, software updates, and training add to the financial burden. Many small-scale farmers may also lack the technical expertise needed to operate, troubleshoot, and maintain robotic systems effectively. Integrating automation into existing farming practices can be challenging, especially in regions with limited access to technical support and digital infrastructure (Duarte *et al.*, 2021).

Furthermore, many robotic systems require stable electricity and internet connectivity for remote monitoring. In rural or developing areas, unreliable power supplies and weak internet connections can limit their effectiveness (Gentry *et al.*, 2017). Most robotic solutions are designed for large aquaculture operations with standardized processes. Small-scale farmers often use diverse, traditional methods that may not be easily adaptable to automation. Customizing robotic technologies for smaller farms may not be financially viable for manufacturers, further restricting accessibility (Føre *et al.*, 2018). Although robotics can enhance sustainability, their environmental footprint, such as electronic waste and energy consumption, must also be considered. Additionally, excessive reliance on automation could reduce employment opportunities in local fishing communities, raising ethical concerns about labor displacement (Soto *et al.*, 2019).

Sensors technology for sustainable fish farming: The advancement of sensor technology has significantly impacted fish farming, enabling intelligent aquaculture (Su *et al.*, 2020). Sensors play a crucial role in drones and robots, collecting data on oxygen levels, salinity, contaminants, turbidity, and water pH while aiding underwater navigation. The sensor industry is expanding rapidly, driven by developments in core sensor technology, modern information systems, cloud computing, and big data platforms. These advances have facilitated the integration of sensors in fish breeding, adult fish growth, aquatic product storage, processing, and intelligent fishery equipment maintenance. Demand is rising for high-performance, multifunctional, cost-effective, miniaturized, and networked sensors with extended service life. This has increased the integration of sensors with modern physics technologies like nanotechnology, laser, infrared, ultrasound, microwave, and optical fiber (Sharma *et al.*, 2019). Additionally, integrating signal detection and processing circuits on a single chip is creating compact, multifunctional, and reliable sensors. Biosensing also presents new opportunities (Moretto and Kalcher, 2014).

The integration of sensor technologies in sustainable fish farming has greatly improved water quality monitoring, feeding automation, and overall aquaculture management. However, despite these benefits, significant challenges remain, particularly for small-scale farmers. The high cost of advanced sensors for monitoring dissolved oxygen, pH, ammonia, and temperature often requires substantial initial investment, making adoption difficult. Ongoing maintenance, calibration, and repairs add further operational costs (Føre *et al.*, 2018). Additionally, smallholder farmers in developing regions may lack access to reliable electricity and internet connectivity, essential for sensor-based systems. Limited technical expertise can also hinder effective data interpretation, leading to underutilization (Martins *et al.*, 2021). Sensors generate vast amounts of data that require proper analysis, yet small-scale farmers may lack software or expertise, resulting in poor decision-making (Dabbene *et al.*, 2014). Environmental factors such as biofouling and salinity fluctuations further impact sensor accuracy, increasing maintenance complexity (Føre *et al.*, 2018).

Nano-vaccinology as a new technology in fish treatment: Nanotechnology converging with biotechnology has made significant progress in biomedicine (Zhao *et al.*, 2014) and expanded its application in vaccinology, giving rise to nanovaccinology (Mamo and Poland, 2012; Zhao *et al.*, 2014). Nanovaccines are vaccines designed with an antigen or a group of antigens containing an appropriate nanoparticle. They are emerging as a new class of vaccines that specifically target infection sites through the immune system, inhibiting the spread of diseases (Vinay *et al.*, 2018). To enhance immunogenicity, nanoparticles serve as carriers and/or adjuvants. Due to the similar scale between nanoparticles and pathogens, they trigger cellular and humoral immune responses (Vinay *et al.*, 2018; Gheibi and Darroudi, 2019). Other advantages include enhanced blood stability, increased immune activation, elimination of booster doses, no need for a cold chain, and active targeting (Gheibi and Darroudi, 2019). Compared to other medicines and vaccines, nanovaccines are more beneficial for disease prevention.

The shift in vaccine production from whole pathogens to protein and peptide antigens reduced side effects but dramatically decreased immunogenicity (Smith *et al.*, 2015). Nanotechnology in aquaculture introduces unique techniques, particularly in vaccinating farmed fish. Nanoparticles offer advantages in vaccine delivery, enhancing fish safety against pathogenic diseases. However, concerns remain about environmental and health risks associated with nanoparticle delivery (Nasr-Eldahan *et al.*, 2021). Vaccination has significantly impacted infectious disease management in aquaculture, yet effective vaccines remain difficult to develop for many diseases (Luis *et al.*, 2019; Shah and Mraz, 2020). The shift from freshwater ponds to sea pens in the 1970s led to the rapid growth of salmon aquaculture. However, high stocking densities and short distances between farms facilitate disease transmission. Epidemic bacterial diseases have often been prevented through excessive antibiotic use, which is not environmentally sustainable (Bhattacharyya *et al.*, 2015).

Despite the recognized biocompatibility of many nanomaterials used in vaccines such as liposomes, polymeric nanoparticles, and lipid-based carriers significant concerns persist regarding the long-term effects of specific inorganic nanoparticles, including gold, silver, and carbon-based variants. Unlike their conventional counterparts, nanomaterials have a tendency to accumulate in vital organs like the liver, spleen, and brain due to their small size. A growing body of research suggests that prolonged exposure to non-biodegradable nanoparticles may trigger cytotoxicity, oxidative stress, and inflammatory responses (Liu *et al.*, 2021).

While lipid nanoparticles used in mRNA vaccines, such as those developed by Pfizer-BioNTech and Moderna, have demonstrated efficient clearance via metabolic pathways, uncertainties remain regarding the biodistribution of newer nanoparticle formulations (Ndeupen *et al.*, 2021). The immune-modulating properties of nanomaterials raise concerns about potential hypersensitivity reactions, autoimmunity, or altered cytokine profiles in susceptible individuals. Certain polymeric nanoparticles have been associated with inflammatory responses due to their surface charge and composition (Zhang *et al.*, 2020).

Beyond human health, the environmental impact of inorganic nanoparticles, particularly metal-based and carbon nanotubes, is alarming due to their potential for persistence and bioaccumulation. Once released into the environment possibly through waste generated during vaccine production these particles may resist degradation, posing risks to microbial communities and higher organisms (Khan *et al.*, 2022).

The introduction of engineered nanomaterials into water systems through improper waste disposal presents serious ecotoxicological threats. Research indicates that nanoparticles such as silver and titanium dioxide can disrupt aquatic ecosystems by reducing microbial diversity and causing oxidative stress in marine organisms (Batley *et al.*, 2020). Additionally, if nanoparticles from vaccine production or expired doses enter agricultural settings, they could negatively impact soil microbiota and hinder plant growth. Some nanomaterials may even alter nutrient uptake in crops, raising concerns about disruptions in the food chain (Rizwan *et al.*, 2019).

Recent innovative for preservation technology

High hydrostatic pressure (HHP): High hydrostatic pressure (HHP) processing (100–1000 MPa) is of growing interest as an alternative technique to conventional thermal treatments because it cannot only inactivate spoilage bacteria and endogenous enzymes that result in the deterioration of food quality, but also has the potential to retain food nutritional and sensorial characteristics (Teixeira *et al*., 2013). Besides, HHP is also an effective measure to control risks associated with food borne parasites and pathogens in foods (Rendueles *et al*., 2011). As for preservation, the benefits of HHP depend on processing parameters including pressure level and holding time, as well as the intrinsic characteristics of the food matrix (Zhou *et al*., 2010). There seem to be a consensus that the safety and stabilization of food can be achieve with applied pressures between 500 and 600 MPa at the pasteurization temperature (Oliveira *et al*., 2017).

Recently, studies have reported on the application of HHP to extend the shelf life of fishery products. Teixeira *et al*. (2014a) indicated that a 2-log CFU/g reduction of initial bacteria was observed in sea bass fillets at 400 MPa for 30 min, which resulted in an extended shelf life. Roco *et al*. (2018) studied the quality changes of pre- and post-rigor palm ruff (Seriolella violacea) subjected to HHP treatments (450 and 550 MPa, 3 and 4 min). Results indicated that HHP processing of chilled fillets in different stages had different impacts on texture, water holding capacity and ultra-structure, but the postmortem deterioration in both pressurized fillets was delayed with a shelf-life extension of 14–23 days. The inhibition of bacterial growth was also observed in ice-stored salmon (*Salmo salar*), cod (*Gadus morhua*) and mackerel (*Scomber scombrus*) (Christensen *et al*., 2017; Rode and Hovda, 2016) when they were treated with HHP. In addition, HHP treatments have the potential to inactivate serine proteinases involved in the degradation of myofibrillar proteins, thus alleviating the textural softening of fish (Qiu *et al*., 2013).

However, HHP seems to promote lipid oxidation in fishery products. Studies have reported a generally accelerated lipid oxidation in many pressurized products, such as salmon and tuna black tiger shrimp (*Penaeus monodon*) (Kaur *et al*., 2016), sea bass (Teixeira *et al*., 2014b) and mackerel (Rode and Hovda, 2016). Medina-Meza *et al*. (2014) suggested that lipid oxidation during pressurization was not due to a simple action on lipids, but rather to the combined effects of oxygen and catalysts including metal-ions, proteins and enzymes. In addition, HHP even at low temperature seems to have an undesirable effect on the color of fishery products. The surface of products become more whitish with higher pressure levels and longer holding time, looking more like a cooked product as reported by Teixeira *et al*. (2014a).

The discoloration caused by HHP may be due to protein modifications as well as pigment degradation (Cheret *et al*., 2005). Gomez-Estaca *et al*. (2018) showed that compared with salmon treated only with HHP, lower TBARS values were observed in pressurized fish covered with an antioxidant edible gelatin film. Therefore, HHP combined with other appropriate preservation technology will better retain the quality of fishery products.

To enhance its effectiveness, researchers explore combinations with other technologies, such as mild heat treatment (high-pressure thermal processing, HPTP), which improves spore inactivation (Tao *et al*., 2020). Additionally, integrating HHP with natural antimicrobial compounds, such as essential oils or bacteriocins, can create synergistic effects, enhancing microbial control while maintaining product quality (Patterson *et al*., 2018). Pulsed electric fields (PEF) and ultraviolet light (UV) have also been explored in tandem with HHP to target microbial resistance mechanisms more comprehensively (Gómez-López *et al*., 2019). These combinations improve food safety, extend shelf life, and minimize nutritional losses, making HHP more viable for commercial adoption across dairy, meat, juice, and seafood industries. Further research is needed to optimize process parameters and assess regulatory and economic feasibility.

Irradiation and pulsed electric field

Irradiation of seafood technology: Ionizing irradiation is used as a food preservation method by the seafood industry to (i) extend product shelf life (by effectively destroying spoilage microorganisms), (ii) improve food safety (by destroying pathogens responsible for food borne illnesses), (iii) delay or eliminate sprouting or ripening and (iv) control insects and invasive pests. Irradiation is achieved using gamma rays, electron beams, or X-rays. The supplied energy abstracts electrons (ionizes) from atoms in the targeted food. Independent research carried out by the World Health Organization and food regulatory agencies in the USA and EU has confirmed that irradiation is safe (FDA, 2021). Gamma irradiation of 2–7 kGy is considered a successful method of preservation since it can reduce the populations of food-borne bacterial pathogens as well as many fish-specific bacterial spoilers, and can extend the shelf life of fish. Due to its penetration depth and uniform dose distribution, gamma irradiation can be used on a large scale and at a high volume. Treatment with electron beams (high-energy electrons) created within electron accelerators works for products that have low thickness as electron beams have a low penetration depth of a few centimeters. Standards and regulations for the operation of irradiation facilities are covered by ISO 14470 and ISO 9001 (Roberts, 2016).

Nowadays, food irradiation is widely applied to several types of food all over the world (spices, fruit, vegetables, meat and poultry). In the USA, for example, on a yearly basis, about 120,000 tons of food and feed destined for human and animal consumption, respectively, are irradiated (Maherani *et al*., 2016). Chouliara *et al.* (2005) monitored changes in VP, irradiated (at 1–3 kGy) sea bream samples stored under refrigeration. Sensory evaluation indicated that compared to the controls, a dosage of 3 kGy tripled the shelf life of sea bream. Mendes *et al.* (2005) reported a 4 days longer shelf life of gamma-irradiated (at 1 or 3 kGy) ice-stored fresh Atlantic horse mackerel compared to controls.

Silva *et al.* (2006) assessed the effects of gamma radiation (1, 5 and 10 kGy) on ice-stored horse mackerel. The electro phoretic patterns of ice-stored horse mackerel muscle proteins was not affected by the -radiation applied, indicating the potential application of this method for fish preservation, provided that sensory evaluation of treated samples will show no adverse effects on product sensory attributes. Ozden *et al.* (2007) determined the effect of -radiation (2.5–5 kGy) on the quality of refrigerated gilthead sea bream. The results indicated that irradiation extended the shelf life of this fish species with the effect increasing with the irradiation dose.

Riebroy *et al.* (2007) evaluated the effects of radiation (up to 6 kGy) on the physicochemical properties, microbial quality and shelf life of a Thai fermented fish mince. The results showed that even though irradiation at 6 kGy inhibited microbial growth, it induced lipid and protein oxidation. Use of a dose of 2 kGy resulted in no negative effects on product quality for ca. 3 weeks. Mbarki *et al.* (2008) studied the effect of irradiation on lipid oxidation, microbial and physicochemical parameters of refrigerated iced bonito over a period of 3 weeks. The results indicated that spoilage microorganisms were eliminated at doses 1.5 kGy. The peroxide value increased with increasing radiation dose, indicating increased oxidation of lipids as a result of irradiation. Based on microbiological, biochemical and textural properties, irradiation at low doses extended product shelf life up to 3 weeks under chilled storage.

Pulsed electric field processing technology: Pulsed electric field (PEF) processing is a non-thermal food preservation technique used mainly for inactivation of microbes as well as in extraction, drying and other mass transfer processes. Pulsed electric field (PEF) technology consists of the application of short pulses of strong electrical currents with a short duration in the range of microseconds to milliseconds and intensity in the order of 10–80 kV/cm with the goal to inhibit microbial growth (Nowosad *et al*., 2020).

When biological cells are exposed to pulsed electrical currents, the permeability of the cell membrane is affected, causing structural changes and local membrane breakdown. This phenomenon is reversible if the pores formed are small compared to the membrane area. Increasing the pulse width and/or number results in an increase in electric field strength (E) and treatment intensity, which, in turn, promotes the formation of large pores in the cell membrane. This causes irreversible damage to the cell membrane, leading to cell death (Gómez *et al*., 2019).

The food product to be processed is placed in a treatment chamber where two electrodes are connected together with a nonconductive material to avoid electrical flow from one to the other. High-voltage electrical pulses are applied to the electrodes, which then conduct the high-intensity electrical pulse to the product placed between the two electrodes, causing, as mentioned above, microbial cell death. Compared to heat treatments, Pulsed electric field (PEF) offers several advantages as it can remove pathogens from unprocessed products without compromising their nutrient content and organoleptic properties. Pulsed electric field food processing is mostly used for the treatment of liquid and semi-solid food mixtures and for the extraction of food constituents (Gómez *et al*., 2019). The pulses of electric beams increase membrane permeability, enhancing, in turn, the efficiency of drying, extraction or diffusion processes involved in salting, marinating, and other fish preservation methods. Exposure to Pulsed electric field (PEF) can inactivate parasites and reduce the moisture content of a tissue. The latter is an important parameter for frozen products, as reduced moisture content reduces the formation of ice crystals and freeze damage. Pulsed electric field can also be used to enhance the extraction of food components with high nutritional value from fish processing by-products (Borderias and Moreno, 2018).

Pulsed electric field (PEF) processing has also been used for the valorization of fish by-products. A high intensity pulsed electric field-assisted method for calcium extraction from fish bones was reported by Zhou *et al.* (2012). Compared to ultrasonic-assisted calcium extraction, pulsed electric field-assisted calcium extraction was more rapid and more efficient. In a similar study, PEF proved to be a rapid, efficient method of extracting chondroitin sulfate (ChS) from fish bones while reducing the waste product and potential pollution of chondroitin extraction (He *et al*., 2014).

He *et al.* (2017) successfully combined Pulsed electric field (PEF) (22.79 kV/cm; 9 pulses) with semi-bionic extraction to improve the efficiency of extracting collagen calcium and ChS from fish bone. Li *et al.* (2016) used pulsed electric field-assisted enzymic protein extraction in abalone visceral tissue. Optimal extraction was observed using 600s, 20 kV/cm, and a 1:4 ratio of tissue to solvent. Compared to enzymic extraction, pulsed electric field (PEF) assisted enzymic extraction was more efficient and exhibited promising emulsifying properties. Nevertheless, the application of Pulsed electric field (PEF) resulted in lower viscosity and foaming properties of the extracted product. Furthermore, pulsed electric field (PEF) processing failed in reducing enzyme activity of the fish. It should be noted that the electrical conductivity of the product is a crucial parameter that limits the application of Pulsed electric field (PEF) to materials with moderate conductivity (vanWyk *et al*., 2019).

In a study by Franco *et al.* (2020), Pulsed electric field (PEF), processing was applied to extract antioxidants from three residues (gills, bones, and heads) of two commercial species (sea bream and sea bass). Three methods of extraction using two solvents (water and methanol) and a water extraction assisted by Pulsed electric field (PEF) were assessed. Of the in vitro antioxidant, methods used to evaluate the extracts, DPPH (2,2-diphenyl-1-picrylhydrazyl), ABTS(2,2′-azino-bis(3-ethylbenzothiazoline-6-sulfonate) radical cation (ABTS$^{\cdot+}$), and FRAP (Ferric-Reducing Antioxidant Power) tests gave the highest antioxidant capacity values for residues from the sea bream species. In general, gills gave the highest antioxidant activity. Results suggest Pulsed electric field (PEF) as an environmentally friendly and economical method for the production of extracts with antioxidant activity from by-products of the fish industry.

Cost-effectiveness and regulatory barriers of irradiation and pulsed electric field: Pulsed Electric Field (PEF) technology is lauded for its exceptional energy efficiency, particularly in the realm of plant tissue modification. The energy expenditure associated with producing damaged plant tissues ranges from a mere 2 to 16 kJ/kg, a striking contrast to traditional methods such as mechanical processing, which demands 20–40 kJ/kg, or heat treatment, exceeding 100 kJ/kg. Economically, the cost of PEF treatment for extracting valuable compounds from various matrices, estimated at just 0.1–0.5 euros per ton for materials like chicory, grape skin, fennel, red beetroot, soybean, or sugar beet, is markedly lower than the 7.5 euros per ton associated with enzymatic methods. Nonetheless, the initial capital investment required for PEF systems can be daunting, with estimates for a 200 kW system ranging from $300,000 to $500,000, excluding ancillary equipment costs.

In parallel, food irradiation a method that employs ionizing radiation to eliminate pathogens and prolong shelf life presents its own complexities. The cost-effectiveness of this technology hinges on variables such as the type of radiation employed (gamma rays, electron beams, or X-rays), the requisite dosage, and the operational scale. Although specific financial data is scarce, it is well understood that establishing irradiation facilities necessitates considerable capital outlay for radiation sources and shielding, alongside ongoing expenses associated with safety protocols and regulatory compliance (Picart-Palmade *et al.*, 2019).

Pulsed Electric Field (PEF), recognized as a non-thermal processing method, has gained traction in various regions, yet its broader adoption is contingent upon regulatory approvals that differ by country. Regulatory agencies often demand substantiated evidence of safety and efficacy, and the absence of standardized regulations can obstruct the widespread implementation of this promising technology.

Conversely, food irradiation is encumbered by stringent global regulations. In the United States, the Food and Drug Administration (FDA) oversees food irradiation, with specific foods sanctioned for treatment at designated dose levels. The European Union similarly enforces its own regulatory framework governing food irradiation. The regulatory landscape presents formidable barriers, including public perception challenges, labeling mandates, and restrictions on the types of food eligible for irradiation (Kempkes, 2017).

Microwave processing technology

Microwaves are the electromagnetic waves having frequency and wavelength in the range of 300 MHz to 300 GHz and 1m to 1mm, respectively (Nagarajarao, 2016). Most of the industrial microwave systems operate at 915 and 2450 MHz (2.45 GHz), whereas home appliances are based on the frequency levels of 2450 MHz (Zhi *et al*., 2017).

The various applications of microwave drying in food processing including seafood sector include microwave assisted hot air drying, pasteurization, sterilization, thawing, microwave vacuum drying, microwave freeze drying, tempering and baking (Nagarajarao, 2016; Chandrasekaran *et al*., 2013). Recently, the microwaves have been extensively used in heating of foods to enhance microbial destruction and promote better product quality. This technology has been accepted by some of the European and Japanese food processing for commercial pasteurization and sterilization of foods, while in North Ameri under partial acceptance (Lee *et al*., 2021; Zhi *et al*., 2017).

Microwave heating is generally based on the dipolar and ionic mechanism and the realignment of polarized dipolar molecules occurs at a speed of million times per second, which causes internal friction of molecul material (Nagarajarao, 2016, 2019). Hot air micro successfully employed for drying of tilapia fish with reduced drying time and improved quality in terms of rehydration ratio (Duan *et al*., 2010). Wu and Maomicrowave drying of grass carp fillets and reported microwave drying method as more efficient method. A significant reduction in drying time of sardine fish (9.5 to 4.25 minutes) has been reported with the increase Microwave power at 60% for 20 s of time has been reported as optimum cooking conditions of trout (*Onchorhyncus mykiss* eating molecules followed by heating of the microwave drying method (200-600 W at 40- (2008) have carried out hot air and increasing microwave power from at 200 to 500 W (Darvishi *et al*., 2013).

Conclusions

The growing global population has led to an increased demand for nutrient-dense food, particularly fish, due to its high protein and nutritional value. In response, aquaculture has become the primary method of meeting this demand, surpassing wild fisheries. Technological advancements such as biofloc technology (BFT), robotic automation, nanovaccinology, and sensor technologies have significantly improved efficiency and sustainability. However, long-term sustainability requires innovative solutions to challenges like resource scarcity and climate change. Preservation and processing techniques play a crucial role in maintaining fish quality, reducing spoilage, and enhancing sustainability. Given fish's perishable nature, proper storage methods are essential to retain its nutritional value and minimize waste. Additionally, processing increases economic value by converting byproducts into useful products such as biofuel and animal feed. Biofloc Technology (BFT) is an eco-friendly approach that converts nitrogenous waste into microbial biomass, improving water quality, enhancing biosecurity, and serving as an alternative feed source. Robotic automation is transforming fish farming by automating feeding, cleaning, and health monitoring, thereby lowering labor costs and operational risks. However, high initial costs and technical complexities limit access for small-scale farmers. Similarly, nanovaccinology has advanced disease prevention through nanovaccines, strengthening immune responses and reducing dependence on antibiotics. Despite its benefits, concerns remain regarding nanoparticle accumulation and environmental impact. Non-thermal preservation methods such as High Hydrostatic Pressure (HHP), ionizing irradiation, pulsed electric fields (PEF), and microwave processing are extending fish shelf life without compromising quality. PEF enhances nutrient extraction and food safety, while HHP and ionizing radiation effectively deactivate spoilage microorganisms. Microwave processing supports drying, sterilization, and thawing, ensuring seafood quality. Despite the promise of these technologies, high upfront costs and regulatory barriers remain significant obstacles to widespread adoption.

Recommendations for researchers and industry practitioners

- Governments, research institutions, and private enterprises should collaborate to advance aquaculture technologies such as biofloc systems, nanovaccinology, and robotic automation. Funding for interdisciplinary research should focus on improving efficiency, reducing costs, and addressing sustainability challenges like climate change and resource depletion.
- Policymakers should establish regulations that encourage sustainable aquaculture practices, including responsible antibiotic use, environmental monitoring, and waste management. Policies should also support small-scale farmers in accessing advanced technologies through subsidies, training, and knowledge-sharing initiatives.
- High capital costs remain a major barrier to adopting robotic automation, nanovaccinology, and non-thermal preservation methods. Public-private partnerships should work toward cost-effective solutions, such as modular automation systems and scalable biofloc technology, to make innovations more accessible, particularly for smallholder farmers.
- To address resource scarcity, research should focus on alternative, eco-friendly feed sources such as insect protein, algae-based feeds, and microbial proteins. Additionally, optimizing biofloc systems can enhance nitrogen recycling and reduce dependence on traditional feedstocks.
- The adoption of nanovaccinology and other emerging technologies should be accompanied by thorough risk assessments, including long-term studies on nanoparticle accumulation in aquatic environments. Regulatory agencies should establish safety guidelines and ethical considerations for integrating nanotechnology into aquaculture.
- To extend fish shelf life and reduce post-harvest losses, investment in non-thermal preservation technologies should be prioritized. Governments and industry leaders should incentivize the adoption of HHP, PEF, and ionizing irradiation by providing financial support and developing standardized safety regulations.
- Training programs should be established to equip aquaculture professionals and small-scale farmers with technical skills related to biofloc technology, robotic automation, and preservation techniques. Partnerships between universities and industry can bridge knowledge gaps and facilitate technology transfer.
- Processing byproducts into high-value products such as biofuels and animal feed should be promoted to minimize waste and enhance economic returns. Incentivizing the creation of fish-based bioproducts can contribute to a more sustainable and profitable aquaculture sector.
- Given the vulnerability of aquaculture to climate change, investments in climate-resilient infrastructure, precision aquaculture, and adaptive breeding programs are essential. Real-time monitoring systems should be implemented to predict and mitigate climate-induced risks such as temperature fluctuations, ocean acidification, and extreme weather events.
- Strengthening consumer awareness regarding the benefits of sustainably farmed fish and processed seafood can drive demand for responsibly produced products. Certification programs and transparent labeling can build consumer trust and incentivize producers to adopt sustainable practices.

Acknowledgements

None.

Novelty Statement

Fish production enhancement and preservation technologies are revolutionizing aquaculture. This review explores innovative methods boosting fish yields sustainably while maintaining quality. Advanced techniques like genetic engineering, smart feeding systems, and eco-friendly preservation ensure fresher, healthier fish. Discover how technology meets tradition for a seafood-rich future.

Author's Contribution

All authors have contributed equally to this full-length of review article.

Conflict of interest

The author have declared no conflict of interest.

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