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Application of extrusion technology in the development of value added fish products: A comprehensive review

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Abstract
Fish and fishery resources represent an invaluable source of high quality proteins, essential amino acids, long-chain omega-3 fatty acids, minerals and bioactive compounds; however, a substantial proportion of low value species and processing by-products remain underutilized in many regions. Extrusion technology has emerged as an efficient, high temperature short time (HTST) process capable of transforming fish raw materials including mince, surimi, protein isolates and by-products into shelf-stable, nutritious and consumer-acceptable value-added products. This review integrates current scientific knowledge on the principles, mechanisms and technological advances in extrusion as applied to fish-based product development. Key aspects such as raw material selection, physicochemical transformations, nutritional retention, techno-functional properties, sensory attributes, product diversification and the influence of processing parameters are comprehensively discussed. Special emphasis is placed on modern innovations such as twin-screw extrusion, co-extrusion, microencapsulation, high-moisture texturization and 3D food printing that enable the incorporation of heat-sensitive bioactive and the creation of texturized seafood analogues. Economic and environmental perspectives highlight the role of extrusion in resource utilization, reduction of post-harvest losses and support for circular economy models. Although issues such as lipid oxidation, flavour masking and reduced expansion at higher fish inclusion levels pose challenges, continuous improvements in formulation science and process optimization offer viable solutions. Overall, extrusion remains a transformative and sustainable platform for producing nutrient-dense, versatile and high value fish products that align with global health, nutrition and sustainability goals.

Keywords: Extrusion technology, value-added fish products, fish by-products utilization, high-temperature short-time processing

1. Introduction
Fish and fishery products constitute one of the most nutritionally valuable groups of foods globally, providing high-quality proteins, essential amino acids, long-chain omega-3 polyunsaturated fatty acids (PUFAs), vitamins, minerals and numerous health-promoting bioactive compounds. These nutritional advantages contribute significantly to food and nutrition security, particularly in coastal and developing regions where fish serves as an accessible and affordable source of animal protein. Global fish consumption has steadily increased over the past five decades, driven by population growth, rising incomes, diversification of diets, improved processing technologies and expanding aquaculture production (FAO, 2022) [20]. Despite this progress, a substantial challenge persists within the fisheries sector: a large proportion of low-value species, trimmings and processing by-products remain underutilized, often being discarded, converted to low-value fishmeal or lost during post-harvest handling.
It is estimated that 30-50% of global fish biomass including heads, bones, skin, frame meat and viscera does not enter the human food chain, representing a major economic loss and a significant source of environmental burden due to waste disposal issues (Suput *et al.*, 2019) [48]. The transformation of such underutilized resources into nutritious, stable and marketable food products is therefore a critical need in modern fisheries management systems. In this

context, extrusion technology has emerged as one of the most effective and versatile processing platforms available to the food industry.

Extrusion is a high-temperature short-time (HTST), energy-efficient, thermo-mechanical process that integrates mixing, kneading, heating, cooking, shearing and shaping in a continuous operation. Originally developed for cereal- and starch-based foods, extrusion has evolved remarkably, enabling the production of a wide spectrum of fish-based products such as fortified pasta, puffed snacks, breakfast cereals, texturized proteins, fish crackers, protein bars, convenient foods and nutritionally enriched aquafeeds. The ability of extrusion to convert high-moisture, perishable fish materials into shelf-stable products with desirable textural, sensory and nutritional properties makes it especially valuable for coastal nations like India, where refrigeration and cold chain access may be limited.

In addition to its functional versatility, extrusion offers numerous advantages including microbial inactivation, improved digestibility, enhanced control over product uniformity, compatibility with a wide range of ingredients, and the capacity to incorporate heat-sensitive nutrients through encapsulation and modern screw configurations. Recent advancements such as twin-screw extruders, high-moisture extrusion, co-extrusion, microencapsulation, nanoencapsulation, and 3D food printing have further expanded the technological frontier, permitting higher fish inclusion levels, more stable omega-3-rich foods, and the development of sophisticated texturized seafood analogues.

Furthermore, the relevance of extrusion extends beyond food quality and innovation. Its role in sustainability, circular economy, waste reduction, and resource valorization aligns directly with global priorities such as the United Nations Sustainable Development Goals (SDGs), particularly SDG 12 (Responsible Consumption and Production) and SDG 14 (Life below Water). By enabling efficient utilization of fish by-products and reducing post-harvest losses, extrusion supports environmentally responsible processing systems and improves economic outcomes for fishers, processors and small-scale industries.

Given these multidimensional benefits, understanding the scientific principles, raw material requirements, processing parameters, nutritional implications, sensory attributes and technological advances in extrusion is essential for researchers, processors and policy-makers aiming to develop innovative, value-added fish products. This review provides a comprehensive and updated synthesis of the current knowledge on extrusion of fish-based foods, offering deeper insights into its technological capabilities, industrial applications challenges and emerging future prospects.

2. Principles of Extrusion

Extrusion is a highly integrated thermo-mechanical process in which mixing, kneading, heating, shearing, cooking and forming occur simultaneously within a single continuous system. The extruder consists of a feed hopper, a heated barrel and one or two rotating screws that convey the blend of raw materials forward through zones of increasing temperature and compression. As the fish-cereal mixture moves along the barrel, it undergoes progressive physicochemical transformations induced by externally applied thermal energy and internally generated mechanical shear. This dual input of energy plasticise the matrix, disrupts native structures and facilitates controlled denaturation of proteins, gelatinization of starches, softening of lipids, and deactivation of derivative enzymes and destruction of microbial contaminants (Guy, 2020; Harper, 1981) [52, 24].

Inside the extruder barrel, pressure may reach levels high enough to convert the food mass into a viscoelastic melt. When this pressurized melt exits through the die, it experiences a sudden drop in pressure from several mega Pascal’s to atmospheric conditions. This abrupt depressurization causes flash evaporation of superheated moisture, resulting in expansion and the formation of a porous cellular structure that gives extruded foods their characteristic texture and low density (Frame, 1994). The magnitude of expansion depends on interactions among temperature, moisture, screw speed, starch composition and protein content. In fish-based formulations, expansion is often lower than in cereal systems because high protein and lipid levels restrict bubble growth and reduce melt viscosity; however, careful manipulation of processing conditions and ingredient composition can compensate for this limitation (Singh *et al*., 2007) [46].

Protein-starch interactions are central to the behaviour of fish-based extrudates. Fish myofibrillar proteins unfold under heat and shear, exposing reactive groups that participate in aggregation and cross-linking. When these proteins interact with gelatinized starch, composite networks form, influencing hardness, cohesiveness and overall structural integrity of the extrudate (Camire, 2011) [10]. Lipids, particularly the polyunsaturated omega-3 fatty acids present in marine fish, play an important role as well. Although they enhance nutritional quality, they may reduce friction within the barrel and limit mechanical energy transfer, which can lower expansion. This is why lipid levels above approximately 4-6% are generally associated with decreased puffing and an increase in product density (Jeyakumari *et al*., 2016) [27].

The type of extruder also governs processing efficiency. Single-screw extruders are simple and economical, but their limited mixing and shear capabilities make them less suitable for high-fat or high-protein formulations derived from fish. Twin-screw extruders, on the other hand, offer superior conveying, mixing and distributive-dispersive shear, allowing processing of materials with higher fish inclusion levels while maintaining uniformity and product quality. Their ability to operate at controlled thermal and mechanical profiles also makes them particularly suitable for advanced applications such as co-extrusion, encapsulation of heat-sensitive oils and high-moisture texturization used in the production of structured seafood analogues (Meuser & Wiedmann, 2016; Palanisamy *et al*., 2019) [36, 40].

The heating regime in extrusion is created through a combination of externally supplied heat and internally generated frictional energy. This configuration enables the characteristic high-temperature short-time (HTST) conditions that preserve nutritional attributes better than conventional long-time heating methods. The residence time of material in the barrel is relatively short, typically on the order of seconds to a minute and a narrow residence time distribution enhances product uniformity while minimizing nutrient degradation (Guy, 2020) [52]. In fish-based systems, this HTST environment offers particular advantages by rapidly inactivating lipases and proteases that otherwise contribute to lipid oxidation and textural deterioration.

Thermal exposure within the extruder may also reduce volatile compounds responsible for fishy odours, thereby improving sensory acceptance (Rathod & Annapure, 2016) [53].

3. Raw Materials for Fish-Based Extrusion

The selection and quality of raw materials play a defining role in determining the structural, nutritional and sensory characteristics of fish-based extruded products. Fish tissues are rich in high-quality proteins, essential amino acids and long-chain polyunsaturated fatty acids, but they also contain high moisture levels, endogenous enzymes and thermolabile lipids that require careful handling during extrusion. Fresh fish mince is commonly used because it provides excellent protein functionality, desirable water-binding behaviour and good emulsification properties. However, its inherent moisture content, typically 75-80%, must be reduced or balanced with dry ingredients to achieve the rheological consistency needed for extrusion processing (Park, 2014) [41]. Boiled fish meat is also widely employed since thermal pre-treatment enhances microbial safety, improves protein digestibility and partially denatures muscle proteins, thereby facilitating their integration into starch-based matrices used for fortified pasta, noodles and expanded snacks.

Surimi and surimi powder represent highly refined sources of myofibrillar proteins that possess superior gelation, water-holding and viscoelastic properties. These characteristics improve texture, cohesiveness and structural stability in extruded products intended for both low moisture snacks and high moisture texturized seafood analogues (Lanier & Lee, 1992) [54]. Another increasingly valuable ingredient is fish protein isolate (FPI), produced through pH-shift solubilization and precipitation. FPIs exhibit excellent emulsifying and foaming capacities and are particularly useful for developing high protein extruded snacks, cereals and nutritional products (Kristinsson & Hultin, 2003) [55]. Fishmeal, although traditionally associated with animal feed, is emerging as a low-cost, nutrient-dense protein source for human foods, especially in regions seeking affordable fortification strategies. Its protein content of 55-72% and high mineral concentration make it suitable for incorporation into extruded blends (Raa, 2015).

One of the significant advantages of extrusion is its ability to utilise fish by-products, including heads, frames, trimmings and skin, which are often discarded despite being rich in collagen, gelatin, minerals and bioactive compounds. Incorporating these by-products into extruded food formulations supports waste reduction and sustainability goals, reduces production costs and enhances the functional and nutritional profile of the final product. Studies have shown that extrusion can effectively process these materials into stable, protein-rich products without compromising microbiological safety (Suput *et al*., 2019) [48].

Cereal flours and starches serve as essential structural bases and interact with fish proteins to form composite matrices that determine expansion, crispness and textural properties. Wheat flour contributes gluten and starch, which enhance elasticity and product integrity, whereas rice flour produces lighter textures and is particularly suitable for gluten-free applications. Corn grits and maize starch promote greater expansion due to their high amylopectin content, while root and tuber starches such as tapioca and potato contribute superior puffing and crispness because of their low amylose-to-amylopectin ratios (Singh *et al*., 2007) [46]. In addition to cereals, plant derived proteins such as soy protein isolate, pea protein and wheat gluten are often blended with fish proteins to improve binding, balance amino acid profiles and adjust rheology.

Functional additives play a critical role in stabilizing nutritional quality and enhancing product performance during extrusion. Lipids, especially omega-3-rich fish oils must be used judiciously because excessive fat reduces barrel friction, lowers shear generation and limits expansion. To mitigate oxidation of polyunsaturated fatty acids during high-temperature processing, natural antioxidants such as tocopherols, rosemary extract and ascorbic acid are often incorporated (Camire, 2011) [10]. Hydrocolloids including xanthan gum, carrageenan and guar gum are used to improve water retention, maintain structural integrity and enhance textural uniformity in both low and high moisture extrudates. Vitamins, mineral premixes, natural pigments and spices further enrich the nutritional and sensory qualities of fish-based extruded foods.

Thus, the integrated use of fish raw materials, plant-based flours, functional additives and stabilizers enables the development of nutritionally enhanced, texturally desirable and shelf-stable extruded products. Effective raw material selection, combined with optimized formulation strategies, is therefore indispensable in meeting consumer expectations and ensuring consistent product performance in commercial fish-based extrusion applications.

4. Nutritional Significance of Fish-Based Extruded Products

Fish-based extruded products are recognized for their superior nutritional value owing to the high-quality proteins, essential amino acids, long-chain omega-3 fatty acids, minerals and bioactive compounds inherent in marine and freshwater species. Fish proteins are highly digestible and possess a well-balanced amino acid profile, particularly rich in lysine, methionine and threonine, which are often limiting in plant-based ingredients. Extrusion induces controlled protein denaturation, unfolding and aggregation, processes that significantly improve enzymatic accessibility and enhance digestibility without major losses in nutritional value when moderate thermal conditions are maintained (Camire, 2011) [10]. The combination of fish proteins with cereal starches enables the development of complementary amino acid profiles, meeting the nutritional needs of children, athletes and nutritionally vulnerable populations (Venugopal & Shahidi, 1995) [56]. This synergy is particularly valuable in regions where cereal-based foods dominate diets and where protein-energy malnutrition remains prevalent.

One of the defining features of fish ingredients is their high content of long-chain omega-3 polyunsaturated fatty acids (PUFAs), especially eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA). These fatty acids confer numerous health benefits including cardio protective, anti-inflammatory, neurodevelopmental and cognitive-enhancing effects (Calder, 2015). However, EPA and DHA are sensitive to heat, oxygen and oxidation. Extrusion, with its high-temperature short-time (HTST) profile, minimizes prolonged heat exposure and thereby facilitates partial retention of omega-3 fatty acids, particularly when processed under optimized temperatures and moisture levels. Studies report that encapsulation of fish oil or inclusion of natural antioxidants can significantly improve the stability of EPA and DHA during extrusion and subsequent storage (Jeyakumari *et al*., 2016) [27]. The inactivation of lipolytic enzymes such as lipases and peroxidases inside the extruder further reduces oxidative degradation, contributing to better retention of bioactive lipids and enhanced shelf stability.

Micronutrient retention is another advantage of fish-based extrudates, as many fish species and by-products provide substantial amounts of calcium, phosphorus, iron, zinc and selenium. Bones, frames, heads and trimmings often discarded during processing contain concentrated minerals that can be incorporated into extruded foods to address micronutrient deficiencies, especially in low income populations (Suput *et al*., 2019) [48]. The HTST conditions of extrusion also preserve several heat-sensitive vitamins better than conventional thermal processing, making extruded products nutritionally advantageous in comparison to fried or oven cooked alternatives (Guy, 2020) [52]. Moreover, bioactive peptides with antioxidant, antihypertensive or immunomodulatory properties may be retained or formed during extrusion as protein hydrolysis and restructuring occur, contributing additional functional benefits to the final product (Kim & Wijesekara, 2010) [57].

From a functional food perspective, extrusion enables the incorporation of supplemental nutrients, fibres, plant proteins and bioactive compounds without compromising product acceptability. This allows the development of fortified snacks, protein-rich pasta, breakfast cereals, texturized seafood analogues and ready-to-eat foods enriched with fish protein isolates, surimi powder or fish oil. Combined with its long storage stability and low water activity, extrusion contributes to the production of nutrient-dense foods capable of supporting public health and addressing the global demand for healthier protein rich convenience products.

5. Functional and Sensory Properties of Fish-Based Extruded Products

The functional and sensory properties of fish-based extruded products are critical determinants of their consumer acceptance and commercial success. During extrusion, complex physicochemical transformations occur, influencing attributes such as water absorption, solubility, viscosity, expansion, hardness, cohesiveness, colour and flavour. These characteristics are shaped by interactions between starches, proteins, lipids and moisture under the combined influence of heat, shear and pressure. Starch gelatinization and protein denaturation are central processes that create a continuous viscoelastic matrix, which governs the textural structure of the final extrudate. In fish-cereal blends, gelatinized starch forms the foundational structure responsible for expansion and crispness, while denatured proteins contribute to binding strength, reduced breakage and improved uniformity (Singh *et al*., 2007) [46]. Protein-starch interactions also influence mechanical properties, with higher levels of fish protein generally reducing expansion because proteins limit bubble formation and stability, resulting in denser and harder textures (Frame, 1994).

Textural attributes such as crunchiness, crispness, hardness, fracturability, springiness and cohesiveness are strongly affected by processing parameters. For instance, higher barrel temperatures and lower feed moisture promote greater expansion and a lighter porous structure, suitable for snack-type products. In contrast, higher moisture levels and moderate temperatures yield denser and chewier textures, appropriate for protein fortified pasta or texturized seafood analogues (Guy, 2020) [52]. Screw speed, die geometry and moisture distribution further influence rheological behaviour, shaping the mechanical strength and microstructure of the extrudate. The partial gelatinization of collagen in fish by-products during extrusion improves binding and enhances chewiness, making collagen-rich raw materials particularly valuable for structured extrudates such as high moisture seafood analogues (Palanisamy *et al*., 2019) [40].

Sensory properties especially flavour, aroma and colour play a decisive role in determining consumer preference. Fish proteins, while nutritionally advantageous, may contribute off-flavours or oxidation related aromas when exposed to heat. Lipid rich species containing polyunsaturated fatty acids are especially prone to hydrolytic rancidity and oxidative degradation during extrusion. Strategies such as the incorporation of natural antioxidants (e.g., tocopherols, rosemary extract), the use of encapsulated fish oil, the selection of mild-flavoured fish species and process optimization help minimize undesirable flavours and improve sensory appeal (Rathod & Annapure, 2016) [53]. Steam flashing at the die also acts to strip volatile compounds responsible for fishy odours, contributing to cleaner flavour profiles in well-processed extrudates.

Colour is another important sensory attribute influenced by both the raw materials and the extrusion environment. Thermal processing may induce browning reactions due to Maillard interactions between proteins and reducing sugars. Natural pigments such as turmeric, paprika, beetroot and spirulina are often added to enhance visual appeal, stabilize colour and mask slight discoloration caused by lipid oxidation or high protein levels (Gómez *et al*., 2020) [58]. The degree of browning or lightness depends on temperature, residence time, ingredient composition and oxygen exposure during processing.

Overall acceptability depends on achieving a balanced combination of texture, colour, flavour and aroma while maintaining nutritional quality. Consumer studies have demonstrated that fish-cereal extrudates can achieve high sensory scores when formulations are optimized for protein level, moisture content and flavouring ingredients (Chillo *et al*., 2008) [14]. The versatility of extrusion allows for the creation of diverse sensory profiles tailored to different markets ranging from crispy fish snacks to chewy fortified pasta and structured seafood analogues. Through precise control of processing parameters and ingredient selection, extrusion can consistently yield fish-based products that meet both nutritional demands and consumer sensory expectations.

6. Extrusion processing parameters and their influence

Extrusion cooking is an intricate process influenced by a series of interdependent parameters, each of which contributes to the structural, nutritional and sensory qualities of the final fish-based extrudate. Barrel temperature is one of the most critical variables because it governs the degree of starch gelatinization, protein denaturation, lipid softening, enzyme inactivation and microbial destruction. Typical extrusion temperatures for fish-cereal blends range from 100 °C to 200 °C, and selecting the correct thermal profile is essential for achieving desired product characteristics.

Excessively high temperatures may accelerate oxidation of polyunsaturated lipids found in fish tissues, compromising flavour and nutritional quality, whereas insufficient heating can lead to incomplete cooking, reduced expansion and poor texture. Moderate temperature regimes between 110 °C and 160 °C are generally considered optimal for balancing expansion, structural integrity and oxidative stability in fish-based systems (Guy, 2020) [52].

Feed moisture content plays an equally important role by affecting viscosity, melt rheology, expansion potential and density of the extrudate. Low moisture levels typically below 15% of result in high shear and greater friction, promoting higher expansion and crispness, characteristics desirable in snack products. Conversely, high moisture levels above 25-30% reduce viscosity and shear, producing denser, more elastic textures more suitable for protein-rich pasta or high moisture texturized seafood analogues (Frame, 1994). In fish-based formulations, optimal moisture levels generally fall between 18% and 22%, enabling sufficient expansion while preventing burning or sticking due to protein coagulation. Moisture distribution during processing also influences bubble formation and stability at the die, thereby affecting the final product's porosity and mouth feel.

Screw speed affects shear rate, mixing efficiency and residence time. Higher screw speeds increase mechanical energy input, improve starch gelatinization and promote uniform structural development, but excessively high speeds can reduce residence time to the point where complete cooking is not achieved. Screw configuration particularly in twin-screw extruders provides additional control over the intensity of mechanical energy. The strategic arrangement of conveying, kneading and reverse elements determines the extent of protein denaturation, lipid dispersion and ingredient homogenization. Twin-screw systems therefore prove advantageous in processing high fat, high protein fish formulations that require enhanced mixing to prevent phase separation and ensure consistent product quality (Meuser & Wiedmann, 2016) [36].

Die geometry also plays a decisive role in shaping the physical characteristics of extruded products. The diameter length to diameter ratio and shape of the die regulate the pressure drop during extrusion, which in turn governs expansion and textural attributes. A narrow die opening induces higher pressure before exit, resulting in more pronounced expansion at the die interface, while larger die openings produce denser structures. For extruded pasta enriched with fish proteins, dies with limited expansion potential are preferable to achieve the desired firmness and surface smoothness (Chillo *et al*., 2008) [14]. Meanwhile, expanded fish snacks benefit from die designs that maximize puffing.

The lipid content of the formulation significantly influences both processing behaviour and product quality. High lipid levels reduce friction within the barrel, limit the mechanical energy imparted to the material and decrease expansion, often leading to harder, denser extrudates. Given that fish proteins and fish oils naturally contain substantial amounts of polyunsaturated fatty acids, lipid levels in fish based extrudates must be carefully controlled and usually maintained below 4-6% for optimal puffing and textural quality (Camire, 2011) [10]. Incorporating antioxidants is essential to counteract the susceptibility of fish lipids to oxidative breakdown at elevated temperatures.

Post-extrusion handling, including drying and cooling, further influences product stability. Once extruded, low moisture products are typically dried to final moisture levels below 10% to maintain crispness, prevent microbial growth and prolong shelf life. Drying must be properly controlled because overly rapid dehydration may cause structural collapse, whereas insufficient drying can lead to microbial instability, especially in fish enriched products (Gómez *et al*., 2020) [58].

7. Technological advances in extrusion for fish based products

Recent advancements in extrusion technology have significantly expanded the scope, efficiency and product quality achievable in fish based processing. Among the most influential innovations is the widespread adoption of twin-screw extrusion, which offers superior mixing, distributive and dispersive shear, improved thermal control and enhanced flexibility in ingredient handling compared to traditional single-screw systems. Twin-screw extruders allow the processing of high protein, high fat fish materials without phase separation or excessive material slippage and are therefore better suited for fish mince, surimi powder, protein isolates and by-product derived ingredients (Meuser & Wiedmann, 2016) [36]. Their modular screw configurations enable precise control over shear intensity and residence time, permitting the development of both expanded low moisture snacks and structured high moisture seafood analogues.

Co-extrusion is another important advancement, wherein a core material such as fish paste, cheese, seasoning gel or sauce is simultaneously encased within an extruded shell. This technique enables manufacturers to produce flavour-rich, nutritionally enhanced composite products that maintain structural integrity while offering innovative sensory profiles. Co-extruded fish snacks or filled pasta products can deliver higher protein levels, improved mouth feel and increased consumer appeal, particularly in markets seeking hybrid foods with layered textures and integrated flavours.

A major technological breakthrough relates to microencapsulation and nanoencapsulation, which have enhanced the stability of heat-sensitive compounds commonly found in fish such as omega-3 fatty acids, antioxidants, peptides and probiotics. Encapsulation using materials such as maltodextrin, whey protein and chitosan or starch derivatives creates protective matrices around sensitive lipids significantly reducing oxidation during extrusion and improving functional retention during storage. As demonstrated in studies on fish oil fortification, encapsulated oils maintain higher retention of EPA and DHA compared to non-encapsulated forms, making them ideal for producing shelf-stable, omega-3-enriched extruded products (Jeyakumari *et al*., 2016) [27].

High moisture extrusion (HME) represents a transformative advancement in the production of texturized seafood analogues, offering the ability to align and density protein structures to mimic the fibrous texture of natural fish muscle. In HME, moisture levels exceed 40%, and controlled cooling dies create laminar protein alignment, resulting in products with enhanced chewiness, elasticity and structural cohesiveness. This technology, originally developed for plant based meat analogues is now being applied to fish proteins to produce structured seafood products capable of meeting rising demand for healthy, sustainable and versatile fish alternatives (Palanisamy *et al*., 2019) [40].

The integration of 3D food printing with extrusion is an emerging frontier that enables unprecedented customization of product shape, nutrient distribution and sensory properties. By combining extrusion based deposition with precision layering, 3D printing offers opportunities to tailor fish based foods for clinical nutrition, elder care, personalized diets and children's products. Shaping, texturizing and nutrient targeting can be controlled with remarkable accuracy, allowing processors to create visually appealing and functionally enhanced foods using fish proteins, hydrocolloids and functional additives (Dankar *et al*., 2018) [19].

Additional advances include the incorporation of real-time process monitoring systems such as near-infrared spectroscopy (NIR), torque monitoring and machine learning based predictive modelling. These tools allow manufacturers to optimize processing conditions, predict product outcomes and reduce waste by achieving finer control over variables such as moisture, viscosity and material flow. Automated feedback systems further enhance process stability, enabling consistent production of high quality fish based extrudates even at industrial scale.

8. Applications of Extrusion in Value-Added Fish Products

Extrusion technology has significantly expanded the range of value added fish products by enabling the transformation of raw fish materials and processing by-products into shelf-stable, nutritionally fortified and sensory acceptable foods. One of the most notable applications is the production of expanded fish-based snacks, where fish mince, surimi powder, fish protein isolates or fishmeal are blended with cereal starches to generate puffed extrudates. These snacks exhibit enhanced protein content, improved amino acid balance and increased mineral density, while offering desirable texture and flavour when processed under optimized thermal and mechanical conditions. The incorporation of spices, natural pigments and seasoning blends further enhances the sensory appeal of these extrudates, catering to regional taste preferences and supporting their growing popularity in international markets (Gómez *et al*., 2020) [58].

Another major application of extrusion is the development of protein-fortified pasta and noodle products. The integration of fish proteins into cereal-based matrices improves the nutritional quality by increasing protein digestibility, enhancing lysine content and elevating mineral levels. When inclusion levels are carefully controlled, fish-enriched pasta maintains desirable cooking properties such as firmness, minimal cooking loss and acceptable texture. Studies have shown that products incorporating surimi, boiled fish meat or fish powder can retain favourable sensory characteristics, provided that formulation and processing parameters are appropriately adjusted (Chillo *et al*., 2008) [14]. This makes extruded fish-fortified pasta suitable for health-oriented markets, school meal programmes and populations requiring improved dietary protein intake.

Extrusion also plays a central role in the production of ready-to-eat breakfast cereals and high-protein nutritional foods. Fish protein isolates or hydrolysed fish proteins can be incorporated into cereal matrices to create nutrient-dense flakes, crisps or bars that appeal to consumers seeking convenient, protein-rich dietary options. These products offer extended shelf stability due to their low moisture content and can be further enhanced with dietary fibres, antioxidants or encapsulated marine lipids to provide functional health benefits (Camire, 2011) [10].

A major industrial use of extrusion is found in the aqua feed and pet food sectors. Extruded fish-based feeds exhibit superior pellet uniformity, water stability, floatability and digestibility. Fishmeal, fish oils and by-products such as trimmings and frames serve as essential protein and lipid sources in aqua feeds for species including salmon, carp, catfish and tilapia. Extrusion ensures complete starch gelatinization, microbial inactivation and controlled lipid incorporation, resulting in pellets with consistent nutritional quality tailored to the growth requirements of cultured species (Riaz, 2000) [43].

Emerging applications include the production of texturized seafood analogues using high moisture extrusion. This technology allows the creation of fibrous structures that mimic the appearance and mouth feel of natural fish muscle, addressing increasing consumer demand for sustainable seafood alternatives. By manipulating moisture content, screw configuration and die cooling, processors can produce structured fish-based products with desirable chewiness, elasticity and sensory attributes (Palanisamy *et al*., 2019) [40].

Additionally, extrusion facilitates the development of functional and therapeutic foods enriched with marine bio actives such as omega-3 fatty acids, peptides and antioxidants. Microencapsulation techniques protect these sensitive compounds during high temperature extrusion, allowing their incorporation into snacks, breakfast cereals and fortified pasta without significant loss of functionality. Such innovations support the production of functional foods with targeted health benefits, including anti-inflammatory, cardio protective and cognitive-enhancing effects (Jeyakumari *et al*., 2016) [27].

9. Economic and Environmental Perspectives

Extrusion technology offers substantial economic and environmental benefits to the fish processing sector by enabling efficient utilization of raw materials, improving production economics and reducing waste. Economically, extrusion is recognized as a cost-effective and energy-efficient process due to its continuous operation, high throughput capacity and reduced labour requirements. The ability to convert low value fish species, trimmings, frames, heads and other by-products into stable, marketable products significantly enhances the profitability of fish processing operations. These by-products, which often account for 30-50 percent of total fish biomass, typically yield low returns when destined for fishmeal or discarded entirely, resulting in economic losses and environmental burdens. Through extrusion, these materials can be transformed into protein-rich snacks, fortified pasta, functional ingredients and aqua feeds, thereby generating higher economic value and supporting industry diversification (Suput *et al*., 2019) [48].

Extrusion also supports small and medium scale enterprises by minimizing the need for extensive cold storage and reducing dependence on skilled labour. Its high temperature short time processing rapidly inactivates enzymes and microorganisms, allowing the production of shelf-stable foods that require minimal post-processing preservation. This feature is particularly advantageous in regions with limited cold-chain infrastructure, enabling wider distribution and reducing post-harvest losses. The flexibility of extrusion further allows rapid product reformulation in response to market demands, enabling manufacturers to diversify their product portfolio with minimal changes in equipment or production layout (Riaz, 2000) [43].

From an environmental standpoint, extrusion contributes significantly to sustainability and resource conservation. By enabling the utilization of underexploited fish species and waste materials, the technology reduces pressure on high value commercial stocks and supports more balanced exploitation of marine and freshwater ecosystems. The conversion of processing waste into value added products also reduces the volume of organic waste entering landfills or aquatic environments, mitigating pollution risks and supporting cleaner processing practices (FAO, 2022) [20]. Extruded products, characterized by low moisture content and high structural stability, reduce the need for refrigeration during storage and transport, thereby lowering energy consumption and carbon emissions associated with cold-chain logistics.

The development of nutritionally enhanced extruded foods also aligns with global public health and sustainability initiatives. Fortified snacks, cereals and pasta enriched with fish proteins or omega-3 fatty acids promote better dietary quality, while extruded aqua feeds support efficient aquaculture systems that rely on nutritionally balanced, environmentally stable pellets. In many regions, the adoption of extruded floating feeds has reduced feed wastage, improved water quality and supported more sustainable aquaculture practices.

Furthermore, advancements such as encapsulation, energy-efficient heating systems and real-time process monitoring and recyclable packaging materials are strengthening the environmental performance of extrusion based processing. As sustainability regulations and consumer preferences continue to evolve, extrusion remains one of the most adaptable technologies capable of meeting environmental, economic and nutritional expectations simultaneously (Gomez *et al*., 2020).

10. Challenges and Future Prospects

Despite its considerable advantages, the application of extrusion technology to fish-based product development presents several challenges that require careful consideration. One of the most significant issues is the susceptibility of fish lipids particularly long-chain omega-3 fatty acids to oxidation during high-temperature processing. Lipid oxidation not only compromises nutritional quality but also generates undesirable flavours, aromas and colours that can reduce product acceptability. Fish raw materials frequently contain endogenous lipases and oxidizing enzymes, which may accelerate oxidation if not properly inactivated before or during extrusion. Although high temperature short time processing helps limit oxidative damage, oxidation can still occur due to the thermo labile nature of polyunsaturated fatty acids. Encapsulation, antioxidant incorporation and modified atmospheric packaging have been widely recommended to mitigate these effects, but further research is needed to improve lipid stability while maintaining product quality (Jeyakumari *et al*., 2016) [27].

Another challenge relates to achieving desirable expansion and texture when high levels of fish proteins are incorporated. Proteins tend to interact with starches in ways that restrict bubble growth and reduce expansion, resulting in denser and harder extrudates. This structural limitation complicates the development of fish rich snacks where high expansion is desirable. Optimizing feed moisture, screw speed, temperature profiles and starch sources can partially offset these challenges, but formulation constraints remain, particularly when using high fat or high protein species. Hydrocolloids, emulsifiers and compatible plant proteins have been investigated for their ability to improve expansion and enhance the machinability of fish-based blends; however, more detailed studies are required to understand their interactions under varying extrusion conditions (Singh *et al*., 2007) [46].

Maintaining consistent quality and standardizing finished products across different batches and processing systems also remains a difficulty. Variability in fish species, chemical composition and seasonal changes in lipid profiles and differences in raw material freshness can influence extrusion behaviour and final product characteristics. The lack of standardized quality metrics for fish-based extrudates further complicates industrial scale implementation and regulatory approval. Establishing standardized formulations, processing parameters and quality indicators is essential to ensure product consistency and safety across diverse manufacturing environments (Meuser & Wiedmann, 2016) [36].

Looking ahead, extrusion technology holds significant potential for innovation within the fish processing sector. Advances in high moisture extrusion offer promising opportunities for producing structured seafood analogues that replicate the texture, appearance and sensory attributes of natural fish muscle. With increasing global demand for sustainable, alternative protein sources, fish based analogues produced through extrusion may play an important role in meeting market needs and providing environmentally friendly seafood options (Palanisamy *et al*., 2019) [40]. Additionally, the integration of artificial intelligence, computational modelling and machine learning is expected to improve process optimization, allowing manufacturers to predict product outcomes, reduce waste and enhance efficiency by fine-tuning variables such as moisture, temperature and screw configuration.

Emerging innovations such as 3D food printing, advanced encapsulation systems, biodegradable packaging materials and energy-efficient extrusion technologies further expand the potential applications and sustainability of fish-based products. These advancements will support the creation of visually appealing, nutrient dense foods with tailored textures, shapes and nutritional compositions. The combination of extrusion with bioactive-rich marine resources also holds promise for the development of functional foods aimed at improving cardiovascular health, reducing inflammation and supporting cognitive development.

11. Conclusion

Extrusion technology has emerged as a highly versatile, efficient and transformative processing method in the development of value-added fish products. Its unique ability to integrate mixing, cooking, shaping and texturizing operations into a single, continuous process makes it particularly suitable for handling fish raw materials that are otherwise perishable, structurally delicate and prone to quality degradation. By converting fish mince, surimi powder, protein isolates and even low value by-products into nutritionally enriched, shelf-stable and sensory acceptable foods, extrusion offers a sustainable pathway to enhance resource utilization, reduce waste and increase profitability across the fish processing sector.

The nutritional advantages of fish-based extruded products are noteworthy, especially their high quality proteins, essential amino acids, bioactive peptides and long-chain omega-3 fatty acids. The high temperature short time nature of extrusion promotes desirable physicochemical changes while limiting the loss of nutrients and improving protein digestibility. Modern advancements such as twin-screw extrusion, high moisture extrusion, encapsulation technologies and 3D food printing further expand the technical possibilities, enabling the production of structured seafood analogues, functional foods and fortified snacks with tailored textures, flavours and nutrient profiles.

However, challenges remain. The thermo labile nature of polyunsaturated fish lipids increases susceptibility to oxidation, while the high protein and fat content of fish can complicate expansion and texture development. Variability in raw material composition and the lack of standardized quality benchmarks also hinder industrial scalability. Despite these limitations, ongoing research and technological innovation continue to improve lipid stabilization, enhance extrusion efficiency and develop adaptive formulations that maintain product quality. The integration of real-time monitoring, machine learning based optimization and sustainable packaging solutions will further strengthen the role of extrusion in modern fish processing.

Overall, extrusion technology plays a crucial role in advancing the fishery sector toward circular economy principles by enabling the full utilization of raw materials, improving nutritional outcomes and supporting environmentally responsible production systems. As global demand rises for healthy, convenient and sustainable protein sources, fish based extruded products are well positioned to meet consumer expectations and drive future innovation in the food industry. Continued research, process optimization and industry collaboration will be essential to unlock the full potential of extrusion for creating high quality, value-added fish products.

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