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Fish waste-derived collagen as functional food: Nutritional properties and bioactive compound

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Abstract
Fish processing industries generate substantial quantities of by-products, including skin, scales, bones, and fins, which are rich sources of collagen with significant potential as functional food ingredients. This mini review comprehensively examines the valorization of fish waste-derived collagen, focusing on its extraction methodologies, nutritional properties, and bioactive characteristics. Fish collagen offers distinct advantages over mammalian sources, including superior bioavailability, absence of zoonotic disease transmission risks, and cultural-religious acceptability. Various extraction techniques, ranging from conventional acid-soluble and pepsin-soluble methods to innovative approaches such as ultrasound-assisted, enzymatic, and deep eutectic solvent extraction, have been developed to optimize collagen recovery from diverse fish waste materials. The nutritional profile of fish collagen is characterized by high glycine, proline, and hydroxyproline content, contributing to its structural integrity and biological functionality. Furthermore, fish collagen and its hydrolysates exhibit remarkable bioactive properties, including antioxidant, antihypertensive, antimicrobial, and wound-healing activities, positioning them as valuable functional food ingredients. This review synthesizes current knowledge on fish waste-derived collagen, highlighting opportunities for sustainable valorization of seafood processing by-products while addressing technological challenges and future research directions in this rapidly evolving field.

Keywords: Bioactive, collagen, fish waste, functional food, nutritional properties

Indtroduction
The global fish processing industry generates millions of tons of by-products annually, representing approximately 30-70% of the total fish weight, depending on the species and processing methods employed (Rajabimashhadi *et al*., 2023; Ideia *et al*., 2020) [12, 27]. These by-products, traditionally discarded or used for low-value applications such as animal feed and fertilizer, comprise valuable biomaterials including skin, scales, bones, fins, and heads that are rich in collagen and other bioactive compounds (Ghalamara *et al*., 2024a; Rajan, 2024) [7, 28]. The environmental burden associated with fish waste disposal, coupled with increasing global demand for sustainable protein sources and functional food ingredients, has catalyzed intensive research into the valorization of these underutilized resources (Orlandi *et al*., 2023; Lian *et al*., 2024; Scheja *et al*., 2024; Filipe *et al*., 2024) [4, 19, 25, 29]. This paradigm shift from waste to wealth aligns with circular economy principles and contributes to the sustainability of the seafood industry while creating economic opportunities through the development of high-value bioproducts (Xu *et al*., 2023; Gaikwad *et al*., 2024) [6, 39].

Collagen, the most abundant structural protein in vertebrates, constitutes a significant proportion of fish by-products and has emerged as a promising biomaterial for diverse applications in food, pharmaceutical, cosmetic, and biomedical industries (Farooq *et al*., 2024) [2]. Fish-derived collagen offers several distinct advantages over conventional mammalian sources, including bovine and porcine collagen, which have dominated the global collagen market for decades (Tawalbeh *et al*., 2025; Mufidah *et al*., 2025) [23, 35]. The absence of religious and cultural restrictions associated with fish collagen makes it universally acceptable across diverse populations, addressing significant market limitations of mammalian collagen (Shaik *et al*., 2024) [30]. Furthermore, fish collagen exhibits reduced risk of zoonotic disease transmission, particularly concerning bovine spongiform encephalopathy and transmissible spongiform encephalopathies that have raised serious health concerns regarding mammalian-derived products (Mufidah *et al*., 2025) [23]. The lower denaturation temperature of fish collagen compared to mammalian collagen facilitates easier extraction and processing, while its superior bioavailability and digestibility enhance its functionality as a nutritional supplement and functional food ingredient (Joy *et al*., 2024) [14].

Despite the promising potential of fish waste-derived collagen, several challenges remain in translating research findings into commercial applications and widespread market adoption (Tawalbeh *et al*., 2025) [35]. Variability in collagen yield, quality, and functional properties depending on fish species, anatomical source, extraction methods, and processing conditions necessitates standardization and optimization of production protocols (Scheja *et al*., 2024; Bavisetty *et al*., 2024) [1, 29]. The development of cost-effective, environmentally friendly, and scalable extraction technologies is crucial for commercial viability and competitiveness with established mammalian collagen products (Silva *et al*., 2024; Orlandi *et al*., 2023; Makgobole *et al*., 2024) [20, 25, 33]. Furthermore, comprehensive characterization of nutritional composition, bioactive properties, safety profiles, and regulatory compliance is essential for consumer acceptance and market penetration (Ghalamara *et al*., 2024b; Kazakova *et al*., 2024) [8, 15]. Addressing these challenges requires multidisciplinary research integrating food science, biotechnology, nutrition, and engineering to develop innovative solutions that maximize the value of fish waste-derived collagen as functional food ingredients (Rajabimashhadi *et al*., 2023) [27].

This review aims to provide a comprehensive overview of current knowledge on fish waste-derived collagen as functional food, with particular emphasis on sources, nutritional properties, and bioactive characteristics (Tawalbeh *et al*., 2025) [35]. By synthesizing recent advances and identifying knowledge gaps, this review to inform future research directions and facilitate the development of sustainable, high-value products from fish processing by-products (Gaikwad *et al*., 2024) [6].

Methodology

This mini review was conducted following a systematic approach to identify, evaluate, and synthesize relevant scientific literature on fish waste-derived collagen as functional food, with emphasis on nutritional properties and bioactivity (Mufidah *et al*., 2025) [23]. A comprehensive literature search was performed using multiple electronic databases, including Web of Science, Scopus, PubMed, ScienceDirect, and Google Scholar, to ensure broad coverage of peer-reviewed publications in this rapidly evolving field (Gaikwad *et al*., 2024) [6]. The search strategy employed a combination of keywords including bioactive, collagen, fish waste, functional food, and nutritional properties to capture relevant studies published primarily between 2020 and 2025 (Joy *et al*., 2024) [14]. This timeframe was selected to focus on recent advances while including seminal works that have shaped current understanding of fish collagen valorization and functional food applications (Wang, 2021) [37, 38].

Source Of Collagen From Fish Waste

Fish processing operations generate diverse by-products that serve as valuable sources of collagen, with skin, scales, bones, and fins representing the primary anatomical materials rich in this structural protein (Farooq *et al*., 2024) [2]. Fish skin, the most extensively studied collagen source, typically contains 20-30% collagen on a dry weight basis and is characterized by a well-organized fibrillar structure that facilitates extraction and processing (Scheja *et al*., 2024) [29]. Various species have been investigated for skin-derived collagen, including cod (*Gadus morhua*), tilapia (*Oreochromis* spp.), salmon (*Salmo salar*), tuna (*Thunnus* spp.), and numerous other commercially important fish (Tran *et al*., 2023) [36]. The collagen content and characteristics of fish skin vary significantly among species, influenced by factors such as habitat temperature, fish age, nutritional status, and anatomical location, with cold-water fish generally exhibiting lower denaturation temperatures compared to warm-water species (Shaik *et al*., 2024; Mufidah *et al*., 2025) [23, 30]. Codfish skin, for instance, has been successfully utilized for collagen extraction using innovative deep eutectic solvent methods, yielding 2.2% collagen with subsequent enzymatic hydrolysis producing bioactive peptides with notable antioxidant and antihypertensive properties (Silva *et al*., 2024) [33].

Fish scales represent another abundant and underutilized source of collagen, offering advantages such as ease of collection, minimal contamination with other tissues, and high collagen content ranging from 40-60% on a dry weight basis (Metin *et al*., 2023; Li *et al*., 2024) [18, 22]. Scales from various species, including golden grey mullet (*Chelon auratus*), *Megalonibea fusca*, tilapia, and sardines, have been investigated for collagen extraction, demonstrating the versatility of this by-product as a collagen source (Feng *et al*., 2024) [3]. The structural composition of fish scales, consisting of an outer mineralized layer and an inner collagenous layer, requires specific pretreatment steps to remove minerals and facilitate collagen extraction (Sibiya, 2025) [31]. Sardine scales, for example, have been successfully valorized through a circular approach for sustainable collagen production, demonstrating applications in both cosmetics and nutrition (Filipe *et al*., 2024) [4]. The optimization of extraction conditions, including buffer concentration, temperature, pH, and time, significantly influences collagen yield from scales, as demonstrated by Taguchi methodological approaches that have achieved collagen purity of 17.14 ± 0.05 mg/g from fish scales (Bavisetty *et al*., 2024) [1].

Fish bones and cartilage constitute additional sources of collagen, although they are less commonly utilized compared to skin and scales due to higher mineral content and more complex extraction requirements (Rajan, 2024) [28]. The collagen content in fish bones varies depending on the degree of mineralization, with younger fish generally containing higher proportions of extractable collagen (Rajabimashhadi *et al*., 2023) [27]. Demineralization pretreatment using acids or chelating agents is essential for bone-derived collagen extraction, adding complexity and cost to the process but potentially yielding high-quality collagen with unique properties (Mufidah *et al*., 2025) [23].

Fish fins, heads, and swim bladders represent emerging sources of collagen that have received increasing attention in recent years, with studies demonstrating successful extraction and characterization of collagen from these materials (Kumar *et al*., 2024) [16]. The utilization of whole undersized unwanted catches, including mixed biomass of skin, fins, and tail, has been explored as a green extraction approach for hydrolyzed collagen peptides, demonstrating the potential for comprehensive valorization of entire fish by-products (Lian *et al*., 2024) [19].

The type of collagen extracted from fish waste is predominantly Type I collagen, characterized by a triple helix structure composed of two α1 chains and one α2 chain, with molecular weights typically ranging from 100-140 kDa for individual α chains (Gaikwad *et al*., 2024) [6]. Type I collagen is the most abundant collagen type in vertebrates and is particularly suitable for functional food applications due to its structural stability, biocompatibility, and bioactivity (Tawalbeh *et al*., 2025) [35]. Some studies have also reported the presence of Type V collagen in fish tissues, although in much smaller quantities compared to Type I (Farooq *et al*., 2024) [2]. The collagen yield from fish waste varies considerably depending on the source material, fish species, and extraction method employed, with reported yields ranging from less than 1% to over 20% on a dry weight basis (Silva *et al*., 2024) [33]. Lumpfish (*Cyclopterus lumpus*) skins, for instance, have been investigated for maximizing collagen yield through optimization of pre-cleaning and extraction methods, demonstrating the importance of process parameters in determining extraction efficiency (Scheja *et al*., 2024) [29].

Species-specific variations in collagen characteristics reflect adaptations to different environmental conditions, particularly water temperature, which influences the thermal stability and functional properties of extracted collagen (Rajabimashhadi *et al*., 2023; Farooq *et al*., 2024; Shaik *et al*., 2024) [2, 27, 30]. Cold-water fish species, such as cod, salmon, and lumpfish, typically produce collagen with lower denaturation temperatures (15-20°C) compared to warm-water species like tilapia and Basa fish (25-35°C), which has implications for processing conditions and end-use applications (Silva *et al*., 2024; Tran *et al*., 2023) [33, 36]. The lower thermal stability of cold-water fish collagen, while potentially limiting some applications, facilitates easier extraction and digestion, potentially enhancing bioavailability and functional food applications (Shaik *et al*., 2024) [30]. Seabass (*Lates calcarifer*) scales, for example, have been studied for collagen extraction using ultrasonication, with pretreatment and extraction conditions significantly affecting yield and physicochemical properties (Bavisetty *et al*., 2024) [1]. The diversity of fish species and anatomical sources available for collagen extraction provides opportunities for tailoring collagen properties to specific functional food applications while contributing to comprehensive valorization of fish processing by-products (Xu *et al*., 2023; Gaikwad *et al*., 2024) [6, 39]. Follow Table 1, collagen can be extracted from fish waste with any part of fish.

Table 1: Source of Collagen and Type of Collagen from Fish Waste

No	Species	Source of Waste	Extraction Method	Type of Collagen	Yield	Ref.
1.	Nile Tilapia (*Oreochromis niloticus*)	Scales	Acid extraction using 0.5 M acetic acid at 4°C.	Type I Collagen	1.2%*	Surya, and Mulyani. (2022) [34]
2.	Atlantic Salmon (*Salmo salar*)	Skin	Acid extraction with acetic acid (0.5 M) followed by purification via salt precipitation.	Type I Collagen	51.3%**	Wang, *et al*., (2021) [37, 38]
3.	Milkfish (*Chanos chanos*)	Bone and fin	Enzymatic extraction using pepsin (from porcine stomach) in an acetic acid medium.	Type I Collagen (Pepsin-Soluble)	10.2%***	Hidayati, *et al*., (2020) [10]
4.	Red Snapper (*Lutjanus campechanus*)	Skin	Acid method using 0.5 M acetic acid, with pre-treatments (alkali and acid) to remove non-collagenous proteins.	Type I Collagen	~45%**	Ibrahim, and Huda (2019) [11]
5.	African Catfish (*Clarias gariepinus*)	Skin and bone	Combined acid-enzyme method: initial extraction with acetic acid, residue re-extracted using pepsin.	Type I Collagen (ASC & PSC)	12.8% (ASC: 8.1% + PSC: 4.7%)*	Nguyen, *et al*., (2021) [24]
6.	Yellowfin Tuna (*Thunnus albacares*)	Fin and skin	Enzymatic extraction using papain enzyme in a phosphate buffer.	Type I Collagen	38.5%***	Jamilah, and Harvinder (2018) [13]
7.	Spiny Shark (*Squalus acanthias*)	Cartilage	Acid extraction using 0.5 M acetic acid after a demineralization pre-treatment with EDTA.	Type II Collagen	65.4%***	Silva, *et al*., (2020) [32]
8.	Catfish (*Pangasius hypophthalmus*)	Skin	Sequential acid extraction using acetic acid with varying time and solvent ratios.	Type I Collagen	22.7%**	Phantong, *et al*., (2021) [26]
9.	Sardine (*Sardinella longiceps*)	Head and bones	Combined method: acid pre-treatment, then extraction using a mixture of acetic acid and pepsin enzyme.	Type I Collagen (Pepsin-Soluble)	15.1%***	Mathew, and Nair (2023) [21]
10.	Orange-Spotted Grouper (*Epinephelus coioides*)	Skin	Extraction using a weak organic acid (lactic acid) as an alternative solvent.	Type I Collagen	41.3% **	Foo, *et al*., (2022) [5]

* (based on wet scale weight)
**(based on dry skin weight)
*** (based on dry material weight)

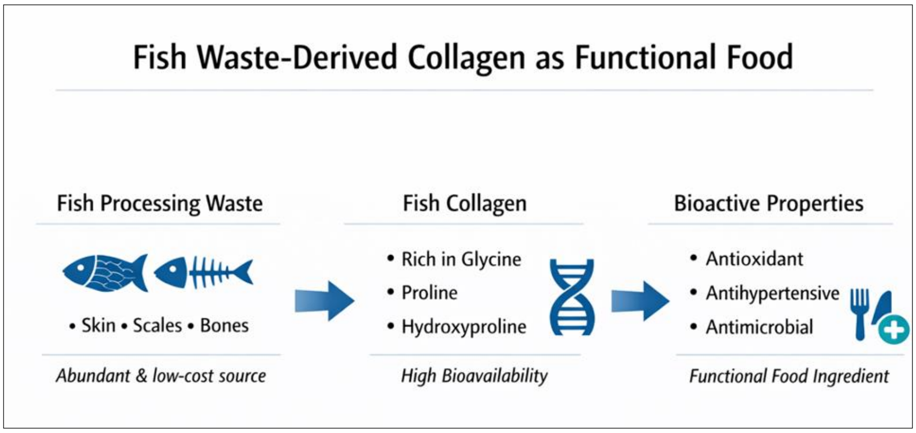

Fig 1: Graphical Abstract

Nutritional Compound

The nutritional value of fish waste-derived collagen is primarily determined by its amino acid composition, which reflects the characteristic structure of collagen proteins and influences both nutritional quality and functional properties (Rajabimashhadi *et al*., 2023) [27]. Fish collagen exhibits a distinctive amino acid profile characterized by high proportions of glycine, proline, and hydroxyproline, which are essential for maintaining the triple helix structure and conferring unique biological properties (Makgobole *et al*., 2024) [20]. Glycine, the smallest amino acid, occupies every third position in the collagen polypeptide chain and typically constitutes 20-33% of total amino acids in fish collagen, facilitating the tight packing of the triple helix structure (Shaik *et al*., 2024) [30]. Fish scale collagen extracted using Tris-Glycine buffer demonstrated high percentages of glycine (20.98%), proline (15.43%), and hydroxyproline (11.51%), indicating fibrous collagen structures characteristic of Type I collagen (Makgobole *et al*., 2024; Rajabimashhadi *et al*., 2023) [20, 27]. Proline and hydroxyproline content is particularly important for collagen stability, with hydroxyproline being unique to collagen and serving as a specific marker for collagen quantification (Shaik *et al*., 2024; Tawalbeh *et al*., 2025) [30, 35]. The combined content of proline and hydroxyproline in fish collagen typically ranges from 15-25%, contributing to the thermal stability and structural integrity of the protein (Farooq *et al*., 2024) [2].

The amino acid composition of fish collagen varies among species, anatomical sources, and extraction methods, reflecting differences in collagen structure and environmental adaptations (Kazakova *et al*., 2024) [15]. Cold-water fish species generally exhibit lower hydroxyproline content compared to warm-water species, which correlates with lower thermal stability and denaturation temperatures (Shaik *et al*., 2024) [30]. The evaluation of nutritional value of freeze-dried hydrolysates obtained from fish skin has demonstrated that processing methods significantly influence amino acid profiles and nutritional quality (Kazakova *et al*., 2024) [15]. Fish collagen is relatively deficient in essential amino acids, particularly tryptophan, which is absent in collagen, and contains limited amounts of methionine and cysteine (Rajabimashhadi *et al*., 2023) [27]. However, fish collagen provides significant amounts of other essential amino acids, including leucine, lysine, phenylalanine, and valine, contributing to its nutritional value as a protein source (Kazakova *et al*., 2024) [15]. The amino acid score and protein digestibility-corrected amino acid score (PDCAAS) of fish collagen are generally lower than those of high-quality proteins such as casein or whey protein due to the absence of tryptophan and limited essential amino acid content (Farooq *et al*., 2024) [2]. Nevertheless, fish collagen can serve as a valuable complementary protein source when combined with other proteins in functional food formulations (Kazakova *et al*., 2024) [15].

The molecular weight distribution of fish collagen and its hydrolysates significantly influences nutritional properties, bioavailability, and functional characteristics (Silva *et al*., 2024) [33]. Native collagen molecules have molecular weights of approximately 300 kDa for the intact triple helix, with individual α chains ranging from 100-140 kDa (Rajabimashhadi *et al*., 2023; Gaikwad *et al*., 2024) [6, 27]. Enzymatic hydrolysis produces collagen peptides with varying molecular weight distributions, typically ranging from less than 1 kDa to over 10 kDa, depending on the degree of hydrolysis and processing conditions (Kuprina *et al*., 2023) [17]. Hydrolyzed collagen peptides from *Mugil cephalus* L. were fractionated into <3 kDa (approximately 5% yield) and >3 kDa (0.04-0.3% yield) fractions, with the lower molecular weight fraction demonstrating significant biological activity (Orlandi *et al*., 2023; Rajabimashhadi *et al*., 2023) [25, 27]. Lower molecular weight peptides generally exhibit enhanced bioavailability and absorption compared to intact collagen or larger peptides, as they can be more readily transported across the intestinal epithelium (Kazakova *et al*., 2024) [15]. The gastrointestinal delivery of codfish skin-derived collagen hydrolysates has been investigated using encapsulation in chitosan-TPP capsules, which released approximately 58% of their content primarily in the intestine, demonstrating strategies for targeted delivery and enhanced bioavailability (Tawalbeh *et al*., 2025) [35].

The protein content and purity of fish collagen preparations vary depending on extraction methods, purification procedures, and source materials (Rajabimashhadi *et al*., 2023) [27]. High-purity collagen preparations typically contain 90-98% protein on a dry weight basis, with minimal contamination from non-collagenous proteins, lipids, or minerals (Metin *et al*., 2023) [22]. The protein content of fish collagen hydrolysates may be lower due to the presence of small peptides and free amino acids that may be lost during processing or purification (Kazakova *et al*., 2024) [15]. The digestibility of fish collagen is generally high, with *in vitro* and *in vivo* studies demonstrating efficient breakdown by gastrointestinal proteases and absorption of resulting peptides and amino acids (Joy *et al*., 2024; Kazakova *et al*., 2024) [14, 15]. The digestion process may influence the bioactive properties of collagen peptides, with some studies reporting that gastrointestinal digestion alters the health benefits of collagen hydrolysates (Silva *et al*., 2024) [33]. The *in vitro* bioaccessibility of unicorn leatherjacket fish (*Aluterus monoceros*) skin collagen peptides prepared using crude collagenase enzyme has been evaluated, providing insights into the fate of collagen peptides during digestion and their potential bioavailability (Kumar *et al*., 2024) [16].

Beyond amino acid composition and protein content, fish collagen may contain trace amounts of minerals, particularly calcium and phosphorus in scale- and bone-derived preparations, which can contribute to nutritional value (Li *et al*., 2024) [18]. The mineral content depends on the effectiveness of demineralization pretreatment, with incomplete demineralization resulting in higher mineral retention (Bavisetty *et al*., 2024) [1]. Fish collagen is virtually free of carbohydrates and contains minimal lipid content after proper defatting pretreatment, making it suitable for low-carbohydrate and low-fat dietary applications (Kazakova *et al*., 2024) [15]. The caloric content of fish collagen is approximately 4 kcal/g, similar to other proteins, and its incorporation into functional foods can contribute to protein fortification without significantly increasing caloric density (Xu *et al*., 2023) [39]. The techno-functional properties of collagen hydrolysates and peptides, including solubility, emulsifying capacity, foaming properties, and water-holding capacity, are influenced by molecular weight distribution, amino acid composition, and degree of hydrolysis, affecting their utility in various food applications (Joy *et al*., 2024) [14]. The combined effects of extraction methods and hydrolysis conditions on functional properties of tilapia scale gelatin hydrolysates have been systematically investigated, demonstrating the importance of processing parameters for optimizing nutritional and functional characteristics (Feng *et al*., 2024; Tawalbeh *et al*., 2025) [3, 35].

Bioactive Compound

Fish waste-derived collagen and its hydrolysates exhibit diverse bioactive properties that extend beyond basic nutritional value, positioning them as promising functional food ingredients with potential health benefits (Ghalamara *et al*., 2024a; Wang, 2021) [7, 37, 38]. Antioxidant activity represents one of the most extensively studied bioactive properties of fish collagen peptides, with numerous studies demonstrating their capacity to scavenge free radicals, inhibit lipid peroxidation, and protect against oxidative stress (Heidari *et al*., 2024) [9]. The antioxidant mechanisms of collagen peptides include direct radical scavenging through donation of hydrogen atoms or electrons, metal ion chelation to prevent pro-oxidant activity, and potential upregulation of endogenous antioxidant enzyme systems (Xu *et al*., 2023) [39]. Codfish skin-derived collagen hydrolysates produced by alcalase treatment demonstrated notable antioxidant activity of 961 µmol Trolox equivalents (TE), indicating strong radical scavenging capacity (Silva *et al*., 2024) [33]. Yellowfin tuna (*Thunnus albacares*) skin collagen extracted using ultrasound-mediated techniques exhibited antioxidant specifications, demonstrating that extraction methods can influence bioactive properties (Heidari *et al*., 2024; Silva *et al*., 2024) [9, 33]. Unicorn leatherjacket fish (*Aluterus monoceros*) skin collagen peptides prepared using crude collagenase enzyme showed antioxidant properties in addition to favorable *in vitro* bioaccessibility (Kumar *et al*., 2024) [16]. The antioxidant activity of collagen peptides is influenced by molecular weight, amino acid composition, and sequence, with smaller peptides and those containing hydrophobic amino acids generally exhibiting enhanced activity (Ghalamara *et al*., 2024a) [7].

Antihypertensive activity, primarily mediated through angiotensin-converting enzyme (ACE) inhibition, represents another important bioactive property of fish collagen peptides with significant implications for cardiovascular health (Xu *et al*., 2023) [39]. ACE is a key enzyme in the renin-angiotensin system that converts angiotensin I to angiotensin II, a potent vasoconstrictor, and degrades bradykinin, a vasodilator, thereby playing a central role in blood pressure regulation (Silva *et al*., 2024) [33]. Collagen peptides can inhibit ACE activity through competitive or non-competitive mechanisms, potentially contributing to blood pressure reduction and cardiovascular protection (Ghalamara *et al*., 2024a) [7]. Codfish skin-derived collagen hydrolysates exhibited 39.3% ACE inhibition, demonstrating significant antihypertensive potential Tawalbeh *et al*., 2025) [35]. The ACE-inhibitory activity of collagen peptides depends on peptide size, amino acid sequence, and the presence of specific amino acids at the C-terminal position, with peptides containing hydrophobic amino acids (particularly proline, leucine, and phenylalanine) at the C-terminus generally exhibiting higher activity (Wang, 2021) [37, 38]. Marine fish-derived proteins and peptides have been recognized as potential antioxidants with diverse bioactive properties relevant to functional food applications (Ghalamara *et al*., 2024a) [7]. The valorization of fish processing by-products for bioactive peptide production has been extensively reviewed, highlighting the biological and functional properties of these compounds Rajabimashhadi *et al*., 2023) [27].

Wound-healing and tissue regeneration properties of fish collagen peptides have been demonstrated in various *in vitro* and *in vivo* studies, suggesting potential applications in functional foods targeting skin health and tissue repair (Orlandi *et al*., 2023) [25]. The T-scratch test, which assesses cell migration and wound closure *in vitro*, has shown positive results for hydrolyzed collagen peptides from *Mugil cephalus* L., with a <3 kDa fraction demonstrating significant effects on human endothelial cells at concentrations as low as 0.13 µg/mL (Tawalbeh *et al*., 2025) [35]. Collagen from *Megalonibea fusca* scales exhibited hemostatic effects, demonstrating potential for wound healing applications (Li *et al*., 2024) [18]. The mechanisms underlying wound-healing properties of collagen peptides include stimulation of cell proliferation and migration, promotion of extracellular matrix synthesis, modulation of growth factor signaling, and potential anti-inflammatory effects (Joy *et al*., 2024) [14]. Fish skin-derived gelatin peptides have been reviewed for their bioactivity and mechanistic insights, with strategies for stability improvement discussed to enhance their functional food applications. The incorporation of collagen peptides into functional foods may support skin health, accelerate wound healing, and promote tissue regeneration through oral supplementation, although more clinical studies are needed to confirm these effects in humans (Tawalbeh *et al*., 2025) [35].

Antimicrobial properties have been reported for some fish collagen peptides, suggesting potential applications in food preservation and as natural antimicrobial agents in functional foods The antimicrobial mechanisms of collagen peptides may include disruption of bacterial cell membranes, interference with essential metabolic processes, and potential immunomodulatory effects that enhance host defense mechanisms (Xu *et al*., 2023) [39]. Peptide compositions based on hydrolysates of collagen-containing fish raw materials have been obtained and studied for various biological activities, including potential antimicrobial effects (Kuprina *et al*., 2023) [17] The antimicrobial activity of collagen peptides varies depending on peptide sequence, size, charge, and hydrophobicity, with cationic and amphipathic peptides generally exhibiting stronger antimicrobial properties. The exploration of fish processing by-products as alternative sources of bioactive peptides has highlighted their potential for food applications, including antimicrobial and preservative functions (Xu *et al*., 2023; Ghalamara *et al*., 2024a) [7, 39]. However, the antimicrobial activity of fish collagen peptides is generally weaker compared to dedicated antimicrobial peptides, and further research is needed to optimize peptide production and characterize antimicrobial mechanisms (Wang, 2021) [37, 38].

Additional bioactive properties of fish collagen peptides include potential anti-inflammatory effects, immunomodulatory activities, bone health promotion, and joint health support. Anti-inflammatory properties may be mediated through inhibition of pro-inflammatory cytokine production, modulation of inflammatory signaling pathways, and potential effects on immune cell function (Xu *et al*., 2023) [39]. The techno-functional and bioactivity properties of collagen hydrolysates and peptides have been comprehensively reviewed, highlighting their diverse biological activities and potential health benefits

(Ghalamara *et al*., 2024a) [7]. The processing technique, physicochemical properties, and bioactive properties of marine collagen have been reviewed, emphasizing the importance of extraction and processing methods for preserving and enhancing bioactivity. The bioactive properties of fish collagen peptides are influenced by multiple factors, including fish species, anatomical source, extraction method, degree of hydrolysis, peptide size distribution, and amino acid composition (Xu *et al*., 2023; Shaik *et al*., 2024) [30, 39]. Optimization of these parameters is essential for maximizing bioactivity and developing effective functional food products based on fish waste-derived collagen. Future research should focus on elucidating structure-activity relationships, identifying specific bioactive peptide sequences, conducting clinical trials to validate health benefits, and developing strategies for enhancing stability and bioavailability of collagen peptides in functional food applications (Tawalbeh *et al*., 2025; Xu *et al*., 2023) [35, 39].

References

1. Bavisetty SCB, Benjakul S, Prodpran T. Ultrasonication on collagen yield, physiochemical and structural properties from seabass (*Lates calcarifer*) scales as affected by pretreatment and extraction conditions. Natural Life Sciences Communications, 2024, 23(1). Article 003. https://doi.org/10.12982/nlsc.2024.003
2. Farooq U, Naz S, Maqsood S, Ahmed MM. A review on marine collagen: Sources, extraction methods, colloids properties, and food applications. Sustainable Chemistry One World, 2024, 3. Article 100027. https://doi.org/10.1186/s42825-024-00152-y
3. Feng L, Jiang T, Wang Y, Li J, Liu Y. Combined effects of gelatin extraction methods and hydrolysis protease types on the functional properties of tilapia scale gelatin hydrolysates. International Journal of Food Science and Technology, 2024, 59(8). Article e17354. https://doi.org/10.1111/ijfs.17354
4. Filipe A, Alves AL, Valente LMP, Oliveira MBPP, Silva AM. Valorizing sardine scales: A circular approach to sustainable collagen for cosmetics and nutrition applications. Frontiers in Pharmacology, 2024, 15. Article 1443358. https://doi.org/10.3389/fphar.2024.1443358
5. Foo SC, Khong NMH, Yusoff FM. Lactic Acid Extraction of Collagen from Grouper (*Epinephelus coioides*) Skin: A Greener Approach and Its Physicochemical Properties. Sustainable Chemistry and Pharmacy,2022:25:100577.
6. Gaikwad KK, Gaikwad RT, Lee YS. Fish by-product collagen extraction using different methods and their application. Marine Drugs, 2024, 22(2). Article 60. https://doi.org/10.3390/md22020060
7. Ghalamara S, Silva S, Brazinha C, Pintado M. Valorization of fish processing by-products: Biological and functional properties of bioactive peptides. Current Food Science and Technology Reports,2024a:2(3):245-260. https://doi.org/10.1007/s43555-024-00045-5
8. Ghalamara S, Silva S, Brazinha C, Pintado M. Exploring fish processing by-products as an alternative source of bioactive peptides: A review on extraction and food applications. Current Food Science and Technology Reports,2024b:2(3):261-278. https://doi.org/10.1007/s43555-024-00041-9
9. Heidari F, Razavi SH, Khodaiyan F. Ultrasound-mediated technique for facilitating collagen recovery from yellowfin (*Thunnus albacares*) skin: Insight into the structure, functional and antioxidant specification. Journal of Aquatic Food Product Technology,2024:33(2):123-138. https://doi.org/10.1080/10498850.2024.2306246
10. Hidayati D, Pratama RA, Nurlimala M. Extraction and Characterization of Pepsin-Soluble Collagen from Milkfish (*Chanos chanos*) Bone and Fin. Indonesian Journal of Marine Sciences,2020:25(1):21-30.
11. Ibrahim SA, Huda N. Extraction and Characterization of Collagen from Red Snapper (*Lutjanus campechanus*) Skin as Influenced by Acetic Acid Concentration. International Journal of Food Properties,2019:22(1):654-666.
12. Ideia P, Pinto J, Ferreira R, Figueiredo L, Spínola V, Castilho PC, *et al*. Fish processing industry residues: A review of valuable products extraction and characterization methods. Waste and Biomass Valorization,2020:11(8):3223-3246. https://doi.org/10.1007/s12649-019-00739-1
13. Jamilah B, Harvinder KG. Properties of Gelatine and Collagen from the Skin and Fin of Yellowfin Tuna (*Thunnus albacares*). Journal of Food Science and Technology,2018:55(10):4020-4030.
14. Joy AT, Surendran-Nair M, Shanmughan VP, Mathew S. A review on fish skin-derived gelatin: Elucidating the gelatin peptides—Preparation, bioactivity, mechanistic insights, and strategies for stability improvement. Foods, 2024, 13(17). Article 2793. https://doi.org/10.3390/foods13172793
15. Kazakova IV, Kuprina EE, Kovalev NN. Evaluation of the nutritional value of freeze-dried hydrolysates obtained from fish skin. Vestnik MGTU,2024:27(3):316-327. https://doi.org/10.21443/1560-9278-2024-27-3-316-327
16. Kumar D, Devi KS, Sharma G. *In vitro* bioaccessibility and antioxidant properties of unicorn leatherjacket fish (*Aluterus monoceros*) skin collagen peptides prepared using crude collagenase enzyme isolated from fish fins. Brazilian Journal of Development, 2024, 10(6). Article 029. https://doi.org/10.34117/bjdv10n6-029
17. Kuprina EE, Sakharov IY, Kovalev NN. Obtaining and study of peptide compositions based on hydrolysates of collagen-containing fish raw materials. Fermentation, 2023, 9(5). Article 458. https://doi.org/10.3390/fermentation9050458
18. Li J, Wang M, Qiao Y, Tian Y, Liu J, Qin S, *et al*. Extraction, characterization, and hemostatic effect of collagen from the scales of *Megalonibea fusca*. Journal of Food Science,2024:89(12):8674-8688. https://doi.org/10.1111/1750-3841.17644
19. Lian PZ, Vang B, Kleppe M, Aas GH, Slizyte R. More sustainable use of aquaculture cleaner fish: Collagen-rich protein hydrolysates from lumpfish (*Cyclopterus lumpus*)—Effects of biomass, pretreatment, and enzyme choice. Frontiers in Sustainable Food Systems, 2024, 8. Article 1346548. https://doi.org/10.3389/fsufs.2024.1346548
20. Makgobole US, Nkosi BVZ, Fosso-Kankeu E. Optimization of collagen extraction from fish scales using Tris-Glycine buffer: A Taguchi methodological approach. Marine Drugs, 2024, 22(12). Article 562. https://doi.org/10.3390/md22120562

21. Mathew P, Nair PG. Optimization of Extraction and Characterization of Collagen from Sardine (*Sardinella longiceps*) Processing Waste. Biocatalysis and Agricultural Biotechnology,2023:47:102576.
22. Metin C, Alparslan Y, Baygar T. Extraction and characterization of acid soluble collagen from golden grey mullet (*Chelon auratus*) scale. Çanakkale Onsekiz Mart University Journal of Marine Sciences and Fisheries,2023:6(2):123-134. https:/doi.org/10.46384/jmsf.1387324
23. Mufidah N, Rahayu D, Elfahmi E. Narrative review: Extraction and characterization of collagen from various fish species. Pharmacon: Jurnal Farmasi Indonesia,2025:21(2):234-248. https://doi.org/10.23917/pharmacon.v21i2.5391
24. Nguyen TT, Heimann K, Zhang W. A Sequential Extraction Method for Collagen from African Catfish (*Clarias gariepinus*) Skin and Bone: Yield and Functional Properties. Waste and Biomass Valorization,2021:12(3):1415-1426.
25. Orlandi V, Calò E, Turroni S, Rampelli S, Renzi S, Salvatore V, *et al*. Green extraction and preliminary biological activity of hydrolyzed collagen peptides (HCPs) obtained from whole undersized unwanted catches (*Mugil cephalus* L.). Molecules, 2023, 28(22). Article 7637. https://doi.org/10.3390/molecules28227637
26. Phantong P, Benjakul S, Kishimura H. Characteristics of Acid-Soluble Collagen from the Skin of Striped Catfish (*Pangasius hypophthalmus*). Journal of the Science of Food and Agriculture,2021:101(4):1362-1369.
27. Rajabimashhadi Z, Gallo N, Salvatore L, Lionetto F. Collagen derived from fish industry waste: Progresses and challenges. Polymers, 2023, 15(3). Article 544. https://doi.org/10.3390/polym15030544
28. Rajan L. Derivatives of structural proteins. In Marine Bioprospecting. Springer, 2024, 89-124. https://doi.org/10.1007/978-981-97-2562-5_4
29. Scheja MD, Slizyte R, Mozuraityte R, Carvajal AK, Rustad T, Aas GH, *et al*. Maximizing collagen yield from underutilized lumpfish (*Cyclopterus lumpus*) skins by optimizing pre-cleaning and extraction methods. Marine Drugs, 2024, 22(12). Article 525. https://doi.org/10.3390/md22120525
30. Shaik MI, Chandra MV, Devi KU, Sarbon NM. A review on the processing technique, physicochemical, and bioactive properties of marine collagen. Journal of Food Science,2024:89(9):5478-5502. https://doi.org/10.1111/1750-3841.17273
31. Sibiya NP. Production, purification and characterisation of fish scale collagen and microbial collagenase and their application in the formation of bioactive collagen peptides [Doctoral dissertation, Durban University of Technology]. DUT Institutional Repository, 2025. https://doi.org/10.51415/10321/6097
32. Silva TH, Moreira-Silva J, Marques ALP, Domingues A, Reis RL. Marine Origin Collagens and Its Potential Applications. Marine Drugs,2020:18(4):214.
33. Silva AFR, Pinto D, Freitas V, Oliveira MBPP, Silva A MS. Gastrointestinal delivery of codfish skin-derived collagen hydrolysates: Deep eutectic solvent extraction and bioactivity analysis. Food Research International, 2024, 176. Article 113729. https://doi.org/10.1016/j.foodres.2023.113729
34. Surya P, Harimawan A, Mulyani S. Isolation and Characterization of Acid-Soluble Collagen from the Scales of Nile Tilapia (*Oreochromis niloticus*). Journal of Aquatic Food Product Technology,2022:31(5):456-468.
35. Tawalbeh DA, Al-Hilal HA, Al-Ismail K. Techno-functional and bioactivity properties of collagen hydrolysate and peptide: A review. Food Reviews International,2025:41(1):1-28. https://doi.org/10.1080/87559129.2025.2450052
36. Tran TT, Ton NMN, Nguyen TTT, Le VVM, Chen C W. Enzyme-assisted extraction and properties of collagen from Basa fish (*Pangasius bocourti*) skin. IOP Conference Series: Earth and Environmental Science, 2023, 1278(1), Article 012008. https://doi.org/10.1088/1755-1315/1278/1/012008
37. Wang L, Liang Q, Chen T, Wang Z. Characterization of Acid-Soluble Collagen from the Skin of Atlantic Salmon (*Salmo salar*) and Its Potential Application. Food Hydrocolloids,2021:112:106358.
38. Wang Y. Natural bioactive compounds from fish. In Bioactive Natural Products. Elsevier, 2021, 467-495. https://doi.org/10.1016/B978-0-12-820655-3.00020-3
39. Xu Y, Han X, Li Y. Improving the sustainability of processing by-products: Extraction and recent biological activities of collagen peptides. Foods, 2023, 12(10). Article 1965. https://doi.org/10.3390/foods12101965