Crimson Publishers
Wings to the Research

Mini Review

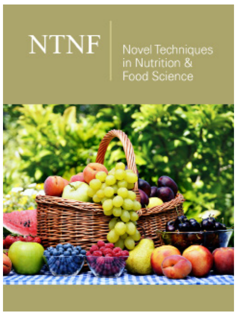
Collagen: A Versatile Protein for Enhancing Food Quality and Nutrition

Romero-Pérez MID[1], Fernández-Escamilla VVA[2] and Estrada-Girón Y[1]*

[1]Department of Chemical Engineering, University Center for Exact Sciences and Engineering, University of Guadalajara, Mexico

[2]Department of Technological Sciences, Ciénega University Center, Mexico

ISSN: 2640-9208



***Corresponding author:** Estrada-GirónY, Department of Engineering, University Center for Exact Sciences and Engineering, University of Guadalajara, Blvd. Marcelino García Barragán 1421, Mexico

Submission: December 04, 2024

Published: December 13, 2024

Volume 8 - Issue 2

How to cite this article: Romero-Pérez MID, Fernández-Escamilla VVA and Estrada-Girón Y*. Collagen: A Versatile Protein for Enhancing Food Quality and Nutrition. Nov Tech Nutri Food Sci. 8(2). NTNF. 000681. 2024.
DOI: 10.31031/NTNF.2024.08.000681

Abstract

Collagen is a type of protein abundant in animals that possesses a unique and complex structure. The relationship among the type of collagen, its structure and function are key factor in understanding its versatility in different fields such as engineering, biomedical, cosmetic, pharmaceutical and food industries, thus, highlighting the adaptable nature of this widespread protein. In this context, for food products, collagen provides various technological functional properties such as thickening, gelling or water binding agents, among others; but recent applications focus on the development of functional foods. Meanwhile, hydrolyzed collagen, with greater digestibility and bioavailability, could fortify diverse types of processed foods to increase their nutritional value in the daily diet, benefiting the health of vulnerable groups at risk of malnutrition. Thus, this minireview focuses collagen, its sources, types of structures and its applications for the development of food products.

Keywords: Collagen; Sources; Uses; Food applications; Future tendency

Introduction

Collagen is one of the most widespread and abundant proteins found in animal bones and skin, making up about 30% of the total protein content [1]. It is an important component of blood vessels, tendons, cartilage, bones and animal skin [2]. The basement membranes and the extracellular matrix of cells are composed of collagen's fibrillar and microfibrillar networks. While connective tissues such as skin, tendons, cartilage and bone also contain these fibrillar proteins [3]. Additionally, collagen reinforces the structure of various organs and tissues because of its strong and stable insoluble fibrils [4]. The market value for collagen and gelatin exceeded approximately 4.7 billion USD in 2020, with 80% utilized by the health and food industries and is expected to grow up to 7 billion USD by 2027 [5]. These statistics are related to the increasing interest of collagen in various industries such as agriculture, tissue engineering, biomedical, cosmetic, pharmaceutical and food, because of its excellent degradability and biological compatibility [6]. For instance, collagen has the ability to form cross-links and self-aggregate, which allows for the creation of stable and durable fibers, ideal for drug delivery systems [7]. While, collagen's natural properties, including biodegradability, hemostatic activity, low allergenicity, high biocompatibility and antigenicity, make it well-suited for pharmacological and medical applications [8]. Particularly, in the food industry, collagen is valuable for developing functional foods and enhancing the quality of processed foods [9]. According to Gómez-Guillén, Giménez, López-Caballero and Montero [10], collagen technological properties can be divided into two main categories: 1) those related to its gelling behavior, including water-binding capacity, gel formation, thickening and texturizing; 2) those linked to its surface behavior, such as film-forming ability, protective colloid function, adhesion and cohesion, stabilization, foam formation and emulsification [9]. Furthermore, there is an increasing interest in the development of innovative functional foods that offer health benefits, as described in sections below.

Despite the diverse uses of collagen, there are still concerns about health risks, such as mad cow disease and cultural or religious restrictions on collagen derived from pigs, which has prompted the exploration of alternative sources such as marine or avian collagen [11]. These alternative sources offer distinct advantages, including lower allergenicity and the absence of zoonotic disease risks associated with mammalian sources. Marine collagen, in particular, is gaining traction due to its high bioavailability, low molecular weight and sustainability. Additionally, fish-derived collagen exhibits excellent antioxidant properties, making it highly suitable for functional food applications and nutraceuticals [12].

Structure and Types of Collagens

Structure of collagen

In 1954, Ramachandran and Karta proposed the structure of collagen, which led to a better understanding of collagen structural and functional properties [7]. The monomeric collagen molecule is known as tropocollagen, which exists in either fibrillar or non-fibrillar types [13]. Mature fibrillar collagen is a long triple-helix domain composed of over one thousand amino acids residues with short non-helical telopeptides at both ends, exemplified by type I collagen [14]. The collagen molecule is a structural protein made up of three helicoidal chains with a characteristic repeating sequence (Gly-X-Y) n, where X is mostly proline and Y is mostly hydroxyproline [15]. Collagen polypeptide chains are primarily composed of glycine (35%) and proline (12%). In contrast, amino acids such as lysine (Lys), arginine (Arg), alanine (Ala), aspartate (Asp) and glutamate (Glu) are less common in collagen. However, hydroxylysine (Hyl) and hydroxyproline (Hyp) are present in significant concentrations, particularly in highly ordered collagen structures [16] The triple-helix structure and its organization into fibers are stabilized by two types of hydrogen bonds. Specifically, these include direct hydrogen bonds between the N-H group of glycine from one chain and the C=O group of the X residue from another chain, as well as indirect hydrogen bonds involving water molecules cos [13]. Thus, water plays a vital role in maintaining the structural integrity of collagen [17,18]. A single type I collagen molecule has a diameter of approximately 1.6nm and a length of about 300nm. Collagen molecules assemble into collagen fibrils with a diameter of around 100nm, displaying a specific pattern known as the D-period [13]. These collagen fibrils then form fibers at the micron scale, which make up collagenous tissues. Collagen fibrils serve as the fundamental components of various collagen-based tissues, while the alignment of collagen fibrils and their organization within a collagen fiber differ across tissues, providing distinct mechanical and biological functions [15].

Collagen types

Collagen is a family of proteins consisting of over twenty-eight distinct types rather than a single protein; moreover, it is also classified into fibrillar and non-fibrillar types. Fibrillar collagens, such as types I, II and III have a molecular weight of approximately 300kDa per molecule and serve as essential structural components in connective tissues, providing tensile strength and rigidity, as seen in tendons, ligaments and bones. Their triple-helical structure weaves into tightly packed fibrils, giving them exceptional mechanical properties [19]. On the other hand, non-fibrillar collagens offer a wider range of structural functions. Type IV collagen, for example, forms a thin network within basement membranes that supports endothelial and epithelial cells. Type VI collagen, forming microfibrils, has a molecular weight of 500-600kDa and is essential for matrix stability in tissues like skin and muscle. Type VII collagen, with a molecular weight around 450kDa, forms anchoring fibrils that secure the dermis and epidermis, ensuring skin integrity [20].

Other types of collagens play critical roles in different tissues and biological processes. Type IX collagen, associated with Type II in cartilage, stabilizes the matrix. Type X participates in cartilage mineralization, while Type XI regulates collagen fibril organization in cartilage. Type XII enhances the tensile strength of tendons and ligaments and Type XIII aids cell adhesion in various cells. Type XIV helps organize the extracellular matrix, Type XVI influences cell-matrix interactions and Type XVIII maintains tissue integrity. The roles of Types XXI-XXVIII collagens vary from facilitating cell connections to specialized functions in nerve tissues and bone formation. However, the function of Type XX collagen remains largely unknown [20,21]. Each type of collagen has a specific function, which is determined by its unique amino acid sequence and post-translational modifications. Such as, type II collagen, present in cartilage, has higher levels of hydroxylysine than that of type I collagen found in bone. Such modifications influence the diameter and packing of fibrils, enhancing cartilage's resilience and shock-absorbing abilities. Similarly, the distinct C-terminal domain of type XVIII collagen interacts with cell integrin receptors to encourage cell adhesion and anchor the collagen network [21]. Type I collagen (Col-I) and Type II collagen have diverse and valuable applications in the food and health industries. Col-I is widely used as a food additive, edible film, coating and supplement. It helps maintain the rheological properties of preserved foods like sausages, enhances emulsification in acidic products and improves the texture of surimi gels. Additionally, Col-I edible films offer a sustainable alternative to plastic coatings, providing resistance to oxidation, discoloration and microbial growth while preserving the sensory qualities of foods [22,23].

Main collagen sources

The most common raw materials for collagen and gelatin extraction are skins or hides, bones, tendons and cartilages. Pig was the first raw material used for the manufacture of gelatin in the 1930s and continues to be the most important material for large scale industrial production. Insects and birds represent alternative sources for collagen extraction [24]. While raw materials from fish and poultry have received considerable attention in recent years, they are still of limited production, making them less competitive in price than mammalian gelatins [10]. With the advances in technology and the search for more sustainable alternatives, collagen is being successfully produced through recombinant protein systems, using bacteria (Streptococcus pyogenes, Escherichia coli), yeast (yeast cells), insects (insect cells), plants (transgenic plants, tobacco), mammalian cells or even synthetic fibrils [25]. However, animal-derived sources remain the most widely used, such as bovine, porcine and marine (fish) collagen [26].

Table 1 summarizes a comparison of the three main sources of collagen: bovine, porcine and marine and characteristics such as amino acids composition, molecular weight, denaturation temperature, bioavailability, health and safe risk, sustainability. Collagen extracted from bovine or porcine typically exhibits higher denaturation temperatures, making it more stable under heat and suitable for industrial applications such as gelatin production for food, pharmaceuticals and cosmetics. In terms of health, both bovine and porcine collagen carry risks of zoonosis and allergies and potential disease transmission such as bovine spongiform encephalopathy that have prompted interest in alternative sources [11] and in addition, the religious restrictions and ethical considerations for porcine collagen. Marine collagen, derived from fish skin, scales and bones, has gained popularity due to its superior bioavailability. Its lower molecular weight allows for faster absorption, making it ideal for dietary supplements and nutraceuticals targeting skin health, joint support and overall wellness. Moreover, marine collagen is more sustainable and environmentally friendly, as it utilizes by-products from the fish processing industry, reducing waste and supporting circular economy practices [35,32]. Finally, the sustainability of marine collagen is notably superior, aligning with environmental recovery efforts, compared to the concerns associated with bovine farming and the ethical limitations of porcine collagen.

Table 1: Comparison of collagen aspects from different sources.

Aspect	Collagen source			Reference
	Bovine collagen	Porcine collagen	Marine collagen	
Primary source	Skin and bones of cows	Skin and bones of pigs	Aquatic vertebrates (mostly fish) and invertebrates (e.g., jellyfish, sponges)	[27,19]
Main amino acids	Glycine, alanine, proline, glutamic acid, hydroxyproline	Glycine, proline, hydroxyproline, glutamic acid, alanine	Glycine, alanine, proline, glutamic acid, serine	[28,29]
Molecular weight	300 kDa (association of 2-3 collagen macromolecules due to intermolecular bonds)	300 kDa, corresponding to its triple-helical structure composed of three α-chains, each with ~100 kDa.	300 kDa (corresponds to a helix of three α-chains, each ~100 kDa)	[30,31]
Physical properties	High mechanical strength and thermal stability; lacks essential amino acids	Similar mechanical strength and thermal stability to bovine collagen; closely resembles human collagen	High bioavailability due to low molecular weight; environmentally friendly and sustainable	[25,27]
Denaturing temperature	Approx. 40.8 °C	Approx. 37 °C	Variable based on species; fish typically around 29 °C	[9]
Health & safety risks	Risk of zoonoses; allergenicity (3% of people allergic)	Risk of zoonoses transmission; cultural/religious restrictions	Free from mammalian zoonoses; minimal toxins and pollutants	[32,33]
Bioavailability	Moderate; lower than marine collagen for its higher molecular weight	Moderate; like bovine	High; fish-derived collagen hydrolysate has enhanced absorption	[25,27]
Medical applications	Hernia repair, tendon reinforcement or reconstructive surgery	Skin healing, plastic surgery, and hernia repair	Bone regeneration and cosmetic applications	[19,34]
Sustainability	Low, with environmental concerns related to animal farming	Moderate sustainability, but limited by ethical concerns	Highly sustainable, aligns with environmental recuperation efforts	[12,27]

Hydrolyzed collagen

Hydrolyzed collagen is a form of collagen that has been broken down into smaller and more easily absorbable peptides. For this reason, its use has increased more rapidly in the food industry. The process of hydrolysis implies the denaturation of large native collagen chains either by enzymatic or chemical method. In its hydrolyzed form, collagen contains eight out of nine essential amino acids along with glycine; and possesses a proline content nearly twenty times greater than that found in other protein-rich foods [10,36]. Chemical hydrolysis involves the use of acidic or alkaline solutions to achieve a similar breakdown. Acid-based extraction is the most commonly used method, as low concentrations of acid can disrupt ionic bonds and Schiff bases between collagen molecules. This non-selective chemical procedure degrades amino acids and breaks non-covalent intermolecular and intramolecular bonds. While alkaline hydrolysis employs a basic solution, typically sodium hydroxide (NaOH), but the process can take various days to weeks to complete. Although alkaline conditions promote high yields of hydrolyzed collagen, it is less advantageous than acid-based extraction since alkaline concentrations can result in the loss of soluble collagen and structural modifications. Beyond that, amino acids containing hydroxyl and sulfhydryl groups may be destroyed during the process [28]. In contrast, enzymatic hydrolysis, often preferred for its precision and gentle conditions, employs proteases such as pepsin, trypsin or alcalase, to cleave peptide bonds within the collagen [10]. These enzymes work by cleaving amino telopeptides from the tropocollagen molecule, breaking crosslinking and allowing the collagen to dissolve. This method is particularly effective in mature tissues, where strong intermolecular bonds have formed as a result of ketoimine crosslinks [28]. Moreover, combining both chemical and enzymatic treatments often achieves better results. Thus, collagen undergoes chemical hydrolysis to produce gelatin, which is subsequently exposed to enzymatic breakdown to yield peptides with specific molecular weights [34]. Furthermore, partially hydrolyzing collagen also produces peptides with molecular weights ranging from 80 to 250kDa, enhancing its functionality and gelation properties. In contrast, extensive hydrolysis yields collagen peptides with molecular weights below 10kDa that often leads to a reduction in functionality [1]. Although the peptide fractions obtained from partially hydrolyzed collagen can vary significantly in their effectiveness for specific biological activities. Henceforward, the type of hydrolysis significantly influences the molecular weight and bioactivity of the resulting peptides, which in turn affects their solubility, antioxidant properties and potential applications [37]. Therefore, key factors in optimizing the hydrolysis process include substrate concentration, enzyme to-substrate ratio, pH and temperature. Such parameters are crucial for achieving efficient reaction rates and obtaining peptides with targeted functional properties [38].

Food enrichment with collagen

Natural collagen production diminishes with age and poor dietary habits, thus, incorporating collagen through dietary intake has become a preferred alternative to maintain adequate levels. For this reason, collagen has become a highly sought-after ingredient in the development of health-focused foods, significantly enhancing their nutritional and functional properties. Despite the lack of well-defined nutritional regulations on collagen supplementation of foods, collagen is widely incorporated into a variety of foods and beverages. Thus, consumers have access to an extensive selection of collagen-based products from various local suppliers [39]. In meat products, collagen enhances emulsifying stability, water-holding capacity and texture, making it a valuable component in sausages, patties and burgers. Studies show that replacing fat with collagen in these products not only improves their texture and moisture retention but also reduces overall fat content, providing a healthier alternative [40]. For fish products, collagen improved the physicochemical properties of sea bream and sardine surimi. Among other applications, edible coating with collagen were evaluated to extend the shelf life of fillets, meat paste, boneless ham and more. This reduces shrinkage while preserving juiciness and acts as a barrier against fat oxidation [41].

In dairy, collagen boosts the viscosity and stability of products like yogurt, preventing whey separation and maintaining a creamy consistency. Collagen-enriched fermented milk products have also demonstrated improved sensory qualities and extended shelf life, while supporting the survival of beneficial probiotics [42]. Hydrolyzed collagen in fermented dairy beverages decreases syneresis and sedimentation, improving physical, chemical and microbiological stability, which is particularly valuable for long-term storage. Additionally, in products like cheese, collagen contributes to textural improvements, making them more appealing and structurally robust [35]. For beverages, collagen acts as a clarifying agent, improving the transparency of juices, beer and wine without compromising their nutritional value. In beer refining, chemically modified bovine collagen not only clarifies but also improves taste, particularly when combined with sweeteners like sucralose and stevia blends [35]. In confectionery, its use in gummy candies and marshmallows enhances texture and extends shelf life, while in baked goods, collagen helps retain moisture, delays staling and improves elasticity [43]. Its ability to inhibit ice crystal formation also makes it valuable in frozen desserts like mousse, ensuring smoother textures and preventing structural damage during storage [44]. Overall, collagen's ability to improve texture, stability and nutritional value across a wide range of food products makes it a key player in food enrichment strategies aimed at meeting consumer demand for healthier functional foods.

Table 2 illustrates functional uses of hydrolyzed collagen in various food products, emphasizing its role beyond structural improvements. It highlights collagen's versatility as an additive, such as its function as a clarifying agent in alcoholic and non-alcoholic beverages and its application in edible films and coatings to enhance product shelf life. From a nutritional perspective, collagen is a significant source of amino acids, including glycine, proline and hydroxyproline, which are essential for maintaining connective tissues, promoting skin health and supporting joint function. Its incorporation into food products enhances their protein profile and provides bioactive peptides with antioxidant and anti-inflammatory properties. These peptides not only contribute to better health outcomes but also align with the growing trend of functional foods aimed at improving overall well-being through dietary choices [49].

Table 2: The applications of hydrolyzed collagen in different products.

Application	Function	Reference
Frankfurt-style sausages	Substituting pork backfat with hydrolyzed collagen improves water-holding capacity, stability after heating and texture (hardness, chewiness), while reducing fat and increasing protein and mineral content.	[45]
Rheological properties of sausages	Collagen improves texture and nutritional fiber levels without affecting sensory properties, reducing fat caps in liverwurst or paste.	[46]
Buffalo patties	Hydrolyzed fish collagen as a fat substitute increases protein content, reduces fat, and maintains cooking yield, water-holding capacity, shrinkage, sensory quality and acceptability.	[35]
Alcoholic beverages	Collagen acts as a clarifying agent, aggregating yeast and insoluble substances in alcoholic beverages.	[34]
Beer refining and yeast preparation	Chemically modified bovine collagen used in beer refining, enhancing taste with sweeteners like sucralose and stevia blends.	[18]

Dairy beverages	Hydrolyzed collagen improves physicochemical and sensory properties, reducing syneresis and sedimentation, while enhancing microbial stability.	[40]
Chrysanthemum beverages	Hydrolyzed collagen improves sensory quality and storage stability when used at proper dosages under ambient pH and temperature conditions.	[47]
Edible films and coatings	Acts as a barrier membrane to prevent oxygen and moisture transfer, enhancing shelf life and improving meat product juiciness. Used in hams, fillets, roasts and sausages.	[16]
Frozen mousse	Gelatin hydrolysate fortifies microstructure and inhibits ice crystal growth, enhancing texture stability.	[42]
Baking materials	Collagen peptides in bread improve water retention, increase volume, delay staleness and extend shelf life by reducing hardness and moisture loss.	[40]
Antioxidant enhancement in baked goods	Marine collagen peptides increase antioxidant properties in biscuits by boosting DPPH radical scavenging activity and ferric reducing power, improving their health benefits.	[48]
Pasting properties in protein-flour mixtures	Collagen and dairy proteins reduce post-gelatinization viscosity, while egg white protein increases it, reflecting differences in water interaction and heat response.	[47]

Future trends towards collagen applications

The current trends in collage applications are driving towards its recognition as a source of bioactive peptides (CPs) thus promoting innovation among various industries. These peptides, derived from hydrolyzed collagen, provide a range of health benefits, including antioxidant, anti-inflammatory and antihypertensive effects. This positions collagen as a fundamental ingredient in the development of functional foods, nutraceuticals and pharmaceutical products [50]. The antioxidant properties of collagen peptides are ideal for combating oxidative stress, a common factor in aging and chronic diseases. By neutralizing Reactive Oxygen Species (ROS) and enhancing the activity of antioxidant enzymes, collagen peptides help protect cells and tissues from damage. This function is particularly valuable in functional foods aimed at promoting skin health and delaying the aging process. Moreover, collagen bioactive peptides have shown potential in managing metabolic disorders, such as type 2 diabetes. These peptides improve glycemic control by inhibiting dipeptidyl peptidase-IV (DPP-IV) activity and stimulating glucagon-like peptide-1 (GLP-1) secretion, which helps regulate blood sugar levels [50].

In addition to its well-documented bioactive potential, collagen is gaining attention in the field of gut health. Studies have demonstrated that collagen peptides can function as prebiotics, promoting the growth of beneficial gut microbiota. Despite challenges, such as variability in production yields and specificity in microbial interaction, CPs hold promise in supporting digestive health. Recent studies have demonstrated their ability to enhance the abundance of gut microbiota genera like Lactobacillus, Akkermansia and Parabacteroides in high-fat diet models, highlighting their role in modulating gut microbiota composition. In the field of food science and technology, most studies on peptides derived from collagen and gelatin have focused on evaluating their antioxidant activity, highlighting their potential as functional ingredients in the development of innovative food products [28]. Peptides are crucial in developing health-oriented functional foods, serving as sweeteners, stabilizers, thickeners, emulsifiers and flavor enhancers. They also improve food quality by enhancing water and oil retention, stability, viscosity and foam generation. Their amphiphilic nature makes them valuable for emulsification, a key property in protein-rich foods [41]. Also, the food packaging industry is also exploring collagen's potential through active packaging materials. Encapsulation technologies using collagen-based films can incorporate bioactive compounds, such as polyphenols, providing antioxidant protection and controlled release properties. These innovations not only extend the shelf life of food products but also deliver functional health benefits [50]. Thus, the versatility of bioactive substances derived from collagen positions it as a crucial ingredient in future health-promoting products. As research progresses, the application of collagen in personalized nutrition and targeted therapies is expected to grow, enabling innovative solutions in disease prevention and health management.

Conclusion

Collagen is a vital protein with diverse applications in multiple industries. Particularly, in the food industry, collagen confers unique functional properties (gelling, emulsifying and stabilizing) that make it an invaluable ingredient in various food products, including dairy, meat and bakery. Besides, it is widely recognized for its ability to improve texture, enhance flavor and extend shelf life when used as an edible coating. The origin of collagen plays a crucial role in determining its suitability for various applications, as its properties differ significantly depending on the source. Despite bovine and pig collagen outstand as the main sources for collagen extraction, the food industry is exploring alternative sources such as fish and plant-based collagen analogs. These efforts will aim to reduce reliance on traditional animal sources, address ethical concerns and mitigate environmental impact, by pursuing more sustainable pathways. In this context, advances in biotechnology and food science have expanded collagen's applications beyond traditional uses. Innovations in hydrolysis and enzymatic treatments are enhancing collagen's bioavailability and efficacy, opening the path for its integration into novel food formulations and supplements. Hydrolyzed collagen, rich in bioactive peptides, improves bioavailability and digestibility, which has become a cornerstone in the development of functional foods. This is because bioactive peptides provide essential amino acids that reduce oxidative stress, enhance join health and skin elasticity and overall wellness. Hence, its nutritional profile positions hydrolyzed collagen as a key component in functional foods and nutraceuticals that meet the needs for health-enhancing dietary products of modern society. Although, priority should be to the dietary needs of vulnerable populations. The future of collagen for food applications is highly promising in different aspects since emerging trends encompass the incorporation of collagen in personalized nutrition, smart packaging or hybrid food products, among others. Consequently, the ongoing exploration of collagen's bioactive potential still has significant contributions to uncover regarding new applications for food products, the health sector and market opportunities.

References

1. Shen X, Zhang M, Bhandari B, Gao Z (2019) Novel technologies in utilization of byproducts of animal food processing: A review. Crit Rev Food Sci Nutr 59(21): 3420-3430.
2. Gisbert VG, Benaglia S, Uhlig MR, Proksch R, Garcia R, et al. (2021) High-speed nanomechanical mapping of the early stages of collagen growth by bimodal force microscopy. ACS Nano 15(1): 1850-1857.
3. Li ZR, Wang B, Chi CF, Zhang QH, Gong YD, et al. (2013) Isolation and characterization of acid soluble collagens and pepsin soluble collagens from the skin and bone of Spanish mackerel (*Scomberomorous niphonius*). Food Hydrocoll 31(1): 103-113.
4. Hennet T (2019) Collagen glycosylation. Curr Opin Struct Biol 56: 131-138.
5. Cao C, Xiao Z, Ge C, Wu Y (2021) Animal by-products collagen and derived peptide, as important components of innovative sustainable food systems-a comprehensive review. Crit Rev Food Sci Nutr 62(31): 8703-8727.
6. Cao J, Wang Q, Ma T, Bao K, Yu X, et al. (2020) Effect of EGCG-gelatin biofilm on the quality and microbial composition of tilapia fillets during chilled storage. Food Chem 305: 125454.
7. Sorushanova A, Delgado LM, Wu Z, Shologu N, Kshirsagar A, et al. (2019) The collagen suprafamily: From biosynthesis to advanced biomaterial development. Adv Mater 31(1): e1801651.
8. Ali AMM, de la Caba K, Prodpran T, Benjakul S (2020) Quality characteristics of fried fish crackers packaged in gelatin bags: Effect of squalene and storage time. Food Hydrocoll 99: 105378.
9. Zhang L, Zhang S, Song H, Li B (2020) Ingestion of collagen hydrolysates alleviates skin chronological aging in an aged mouse model by increasing collagen synthesis. Food Funct 11(6): 5573-5580.
10. Gomez GM, Gimenez B, Lopez CMA, Montero M (2011) Functional and bioactive properties of collagen and gelatin from alternative sources: A review. Food Hydrocoll 25(8): 1813-1827.
11. Mohammad AW, Suhimi NM, Aziz AGKA, Jahim JM (2014) Process for production of hydrolysed collagen from agriculture resources: Potential for further development. J Appl Sci 14(12): 1319-1323.
12. Coppola D, Oliviero M, Vitale GA, Lauritano C, Ambra DI, et al. (2020) Marine collagen from alternative and sustainable sources: Extraction, processing and applications. Mar Drugs 18(14): 214.
13. Ramachandran GN, Kartha G (1954) Structure of collagen. Nature 174(4423): 269-270.
14. Orgel JP, Irving TC, Miller A, Wess TJ (2006) Microfibrillar structure of type I collagen *in situ*. Proc Natl Acad Sci USA 103(24): 9001-9005.
15. Gautieri A, Vesentini S, Redaelli A, Buehler MJ (2011) Hierarchical structure and nanomechanics of collagen microfibrils from the atomistic scale up. Nano Lett 11(2): 757-766.
16. Ketnawa S, Benjakul S, Martínez AO, Rawdkuen S (2017) Fish skin gelatin hydrolysates produced by visceral peptidase and bovine trypsin: Bioactivity and stability. Food Chem 215: 383-390.
17. Shoulders MD, Raines RT (2009) Collagen structure and stability. Annu Rev Biochem 78: 929-958.
18. Nguyen TT, Happillon T, Feru J, Brassart PS, Angiboust JF, et al. (2013) Raman comparison of skin dermis of different ages: Focus on spectral markers of collagen hydration. J Raman Spectrosc 44(9): 1230-1237.
19. Song WK, Liu D, Sun LL, Li BF, Hou H (2019) Physicochemical and biocompatibility properties of type I collagen from the skin of Nile tilapia (*Oreochromis niloticus*) for biomedical applications. Mar Drugs 17(3): 137.
20. Willumsen N, Thorlacius UJ, Karsdal MA (2023) Type XX collagen. In: Biochemistry of Collagens, Laminins and Elastin: Structure, Function and Biomarkers, Third Edition. Elsevier, pp. 181-185.
21. Felician FF, Xia C, Qi W, Xu H (2018) Collagen from marine biological sources and medical applications. Chem Biodivers 15(5): e1700557.
22. Pates G, White T, Durkee S, Saiyed Z (2023) UC-II® undenatured type II collagen data show retention during functional food and beverage prototype processing. Data Brief 48: 109216.
23. Zhao Y, Lu K, Piao X, Song Y, Wang L, et al. (2023) Collagens for surimi gel fortification: Type-dependent effects and the difference between type I and type II. Food Chem 407: 135157.
24. Silvipriya KS, Krishna KK, Bhat AR, Dinesh KB, John A, et al. (2015) Collagen: Animal sources and biomedical application. J Appl Pharm Sci 5:123-127.
25. Coppola D, Oliviero M, Vitale GA, Lauritano C, Ambra DI, et al. (2020) Marine collagen from alternative and sustainable sources: Extraction, processing and applications. Mar Drugs 18(4): 214.
26. Fertala A (2020) Three decades of research on recombinant collagens: Reinventing the wheel or developing new biomedical products? Bioengineering 7(4): 155.
27. Woo MJB, Tunku Abdul RU (2019) Preparation of biomaterials using fish collagen and seaweed alginate to promote *in vivo* cell growth and proliferation activity. Woo Mun Jeng.
28. Amirrah IN, Lokanathan Y, Zulkiflee I, Wee MFMR, Motta A, et al. (2022) A comprehensive review on collagen type I development of biomaterials for tissue engineering: From biosynthesis to bioscaffold. Biomedicines 10(9): 2307.
29. Carvalho AM, Marques AP, Silva TH, Reis RL (2018) Evaluation of the potential of collagen from codfish skin as a biomaterial for biomedical applications. Mar Drugs 16(12): 495.
30. Kumar S, Sugihara F, Suzuki K, Inoue N, Venkateswarathirukumara S, et al. (2015) A double-blind, placebo-controlled, randomised, clinical study on the effectiveness of collagen peptide on osteoarthritis. J Sci Food Agric 95(4): 702-707.
31. Egorikhina MN, Semenycheva LL, Chasova VO, Bronnikova II, Rubtsova YP, et al. (2021) Changes in the molecular characteristics of bovine and marine collagen in the presence of proteolytic enzymes as a stage used in scaffold formation. Mar Drugs 19(9): 502.
32. Oslan SNH, Li CX, Shapawi R, Mokhtar RAM, Noordin WNM, et al. (2022) Extraction and characterization of bioactive fish by-product collagen as promising for potential wound healing agent in pharmaceutical applications: Current trend and future perspective. Int J Food Sci 2022: 9437878.
33. Sadhasivam S, Vinayagam V, Balasubramaniyan M (2020) Recent advancement in biogenic synthesis of iron nanoparticles. J Mol Struct 1217.
34. Lim YP, Mohammad AW (2011) Physicochemical properties of mammalian gelatin in relation to membrane process requirement. Food Bioproc Tech 4: 304-311.
35. Ismail FM, Mat YM, Shukri R, Nur IF, Rashedi IFM, et al. (2018) Effects of Fish Collagen Hydrolysate (FCH) as fat replacer in the production of buffalo patties. J Adv Res Appl Sci Eng Tech 11: 108-117.

36. Bilek SE, Bayram SK (2015) Fruit juice drink production containing hydrolyzed collagen. J Funct Foods 14: 562-569.
37. Al Hajj W, Salla M, Krayem M, Khaled S, Hassan HF, et al. (2024) Hydrolyzed collagen: Exploring its applications in the food and beverage industries and assessing its impact on human health-A comprehensive review. Heliyon 10(16): e36433.
38. An K, Liu H, Guo S, Kumar DNT, Wang Q, et al. (2010) Preparation of fish gelatin and fish gelatin/poly(L-lactide) nanofibers by electrospinning. Int J Biol Macromol 47(3): 380-388.
39. Jafari H, Lista A, Siekapen MM, Ghaffari BP, Nie L, et al. (2020) Fish collagen: Extraction, characterization and applications for biomaterials engineering. Polymers (Basel) 12(10): 2230.
40. Sang S, Ou C, Fu Y, Su X, Jin Y, et al. (2022) Complexation of fish skin gelatin with glutentin and its effect on the properties of wheat dough and bread. Food Chem X 14.
41. Zaky AA, Simal GJ, Eun JB, Shim JH, Abd El AA, et al. (2022) Bioactivities, applications, safety and health benefits of bioactive peptides from food and by-products: A review. Front Nutr 8: 815640.
42. Znamirowska A, Szajnar K, Pawlos M (2020) Probiotic fermented milk with collagen. Dairy 1: 126-134.
43. Kumar S, Kumar R, Nambi E (2015) Effect of pectin methyl esterase and Ca^{2+} ions on the quality of fresh-cut strawberry.
44. Almeida PF, Lannes SC da S (2017) Effects of chicken by-product gelatin on the physicochemical properties and texture of chocolate spread. J Texture Stud 48(5): 392-402.
45. Sousa SC, Fragoso SP, Penna CRA, Arcanjo NMO, Silva FAP, et al. (2017) Quality parameters of frankfurter-type sausages with partial replacement of fat by hydrolyzed collagen. LWT 76: 320-325.
46. Hashim P, Mohd Ridzwan MS, Bakar J, Mat Hashim D (2015) Collagen in food and beverage industries. Int Food Res J 22(1): 1-8.
47. Desert C, Guérin DC, Nau F, Jan G, Val F, et al. (2001) Comparison of different electrophoretic separations of hen egg white proteins. J Agric Food Chem 49(10): 4553-4561.
48. Kumar A, Elavarasan K, Hanjabam MD, Binsi PK, Mohan CO, et al. (2019) Marine collagen peptide as a fortificant for biscuit: Effects on biscuit attributes. LWT 109: 450-456.
49. Jridi M, Abdelhedi O, Souissi N, Kammoun M, Nasri M, et al. (2015) Improvement of the physicochemical, textural and sensory properties of meat sausage by edible cuttlefish gelatin addition. Food Biosci 12: 67-72.
50. Cao N, Fu Y, He J (2007) Preparation and physical properties of soy protein isolate and gelatin composite films. Food Hydrocoll 21(7): 1153-1162.