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Gelatin Recovery from Fish Biowaste for Industrial Application

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Abstract: The aquaculture and fisheries industries are famed for producing wholesome waste and/or by-products, mostly underrated or downgraded to insignificant grounds. Even so, this ignored sector fosters high-price bioactive molecules that exhibit value added derivatives and their invaluable applications. Reinforcement of the blue economy along with vibrant expansion of fisheries prioritizes a wild as well as sustainable exploitation of marine resources. The increasing demand for sustainable and eco-friendly practices in various industries has led to a growing interest in the utilization of biowaste, particularly from the fishing industry. Fish biowaste, including skin, bones, and scales, is rich in valuable compounds such as gelatin, a protein with diverse applications in food, pharmaceuticals, cosmetics, and agriculture. Recovering gelatin from fish biowaste not only provides a sustainable solution for waste management but also offers a promising alternative to traditional mammalian-derived gelatin. Fish gelatin is a propitious substitute to innate gelatin, which faces religious restrictions. Gelatin derived from fish skin and bones is recognized for being biodegradable, with good film-forming capacity, making it a potential replacement for natural gelatin. Applications include edible coatings, microencapsulation and active packaging, benefiting from gelatin's antioxidant and antimicrobial qualities. In this review article, we discuss a comprehensive summary of gelatin recovered from fish biowastes and their recent multifarious advances.

Keywords: *Agriculture, Aquaculture, Biocompatibility, Biopolymers, Biomedical, Cosmetics, Drug Delivery, Fisheries, Gelatin, Hydrogels, Pharmaceuticals, Polyhydroxyalkanoates, Protein Hydrolysates, Waste.*

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I. INTRODUCTION

The increasing global waste generation poses a significant environmental threat, but waste-to-wealth technologies offer a solution by transforming biowaste into valuable biomaterials and energy [42] (Fig. 1). Biowaste can be converted into various biomaterials, such as collagen, chitosan, gelatin, and cellulose, through bioprocessing, supporting a circular bioeconomy. The development of bio-based polymers and biocomposites from renewable resources has potential applications in various sectors, including biomedical, automotive, packaging, and healthcare, promoting sustainability and waste reduction [1]. The increasing demand for sustainable and eco-friendly practices in various industries has led to a growing interest in the utilization of biowaste, particularly from the fishing industry. Fish biowaste, including skin, bones, and scales, is rich in valuable compounds such as gelatin, a protein with diverse applications in food, pharmaceuticals, cosmetics, and agriculture [43]. Recovering gelatin from fish biowaste not only provides a sustainable solution for waste management but also offers a promising alternative to traditional mammalian-derived gelatin. Fish gelatin is a promising alternative to mammalian gelatin, which faces religious restrictions. Researchers have used various methods to enhance fish gelatin's properties, including active compounds, enzymes, crosslinking agents, and nonthermal treatments. These enhancements have improved fish gelatin's gel strength, gelling temperature, and melting point, making it a viable substitute for mammalian gelatin in industrial applications [2] [44].

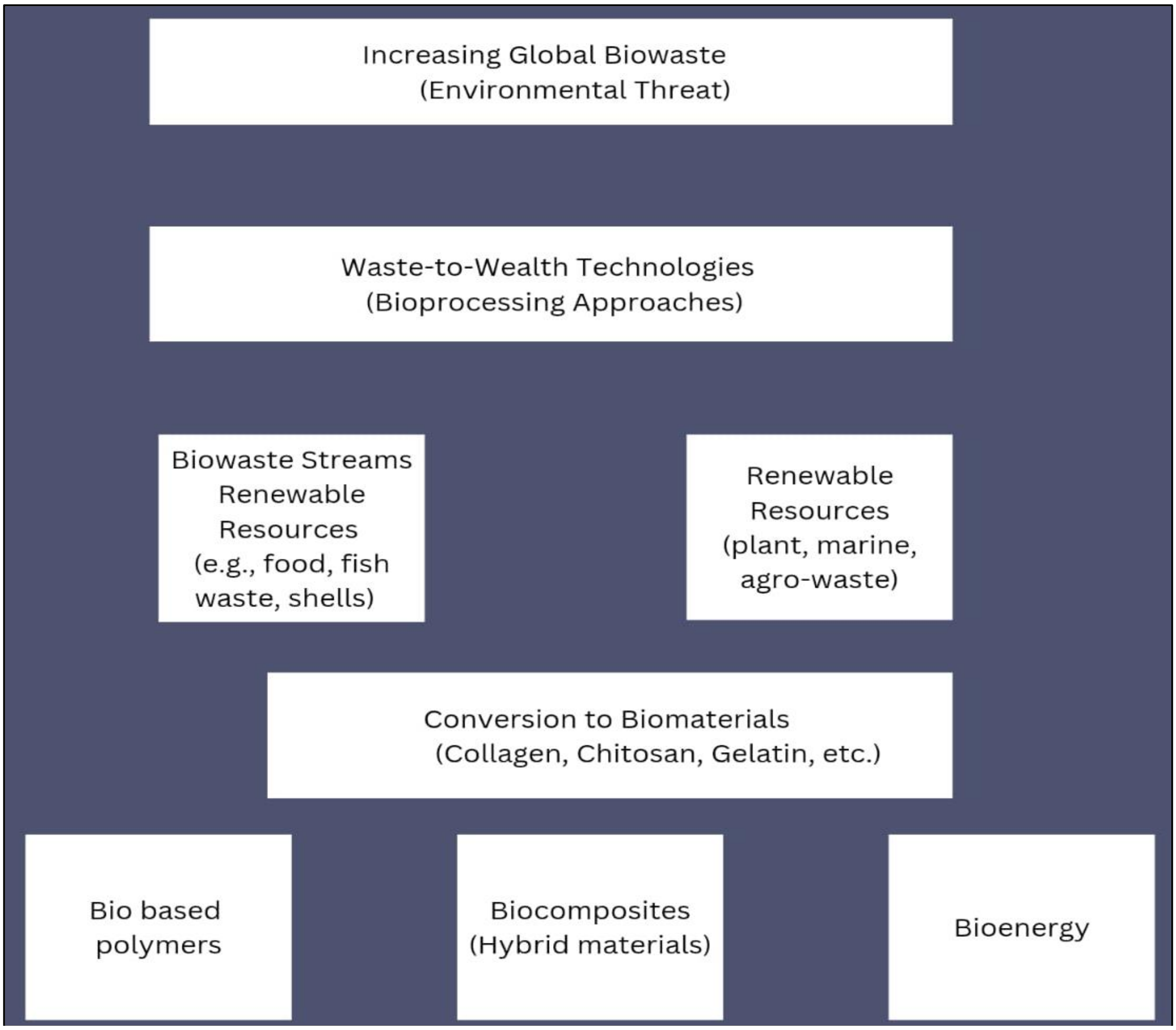

Fig 1 Waste to Wealth: Emerging Green by-Products

Researchers explored fish skin gelatin (FG) from sea bream as an alternative to bovine gelatin (BG). Adding grape pomace (GP) extract to FG improved its gelling and melting properties, with 20% GP showing the best results [3]. The enhanced FG demonstrates potential for use in the confectionery industry due to its improved rheological properties [46].

Fishery waste can be sustainably transformed into high-value compounds like chitosan and fish gelatin [4].The study achieved significant yields of chitosan (20.45%) and gelatin (11.82% from skin, 2.31% from bone) through optimized extraction processes. The resulting chitosan-gelatin biopolymers showed strong antibacterial activity, making them suitable for potential use in eco-friendly food packaging solutions [45].

Gelatin demand has increased globally due to its excellent functional characteristics and applications in various industries, including food and pharmacology [5]. Animal-based agri-food gelatin is widely used in industries due to its abundance, economic value, and versatility as a coating material, food additive, stabilizer, and clarification agent [47]. Gelatin has significant applications in pharmacology, including wound dressings, tissue engineering, and drug delivery, highlighting its potential for valorization and sustainable utilization in various industries. Fish processing generates significant biological waste, which can cause environmental pollution if not utilized properly [6]. Researchers converted fish waste into nutrient-rich fish hydrolysate using *Bacillus subtilis* and *Bacillus thuringiensis*, and found it promoted plant growth in chilli and cowpea. The fish hydrolysate improved plant traits, increased nutrient content, and enhanced soil fertility, offering a potential eco-friendly alternative to chemical fertilizers [48]. Researchers extracted gelatin from fish scales (Rohu and Silver Carp) using chemical and microbial methods, and prepared beads from the extracted gelatin. The gelatin beads remained stable and didn't degrade, unlike commercial gelatin, and showed potential as carriers for antibiotics and fertilizers [50]. The study suggested that gelatin beads can be used as a novel delivery system for fertilizers and antibiotics in agriculture, offering a promising advancement in the field [4] [49]. Fish can be used as a raw material for industrial production of various products, beyond just consumption. Around 19 products derived from

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fish have been identified, including conventional products like fish oil, gelatin, and fish meal, as well as non-conventional products like antimicrobial proteins and bioplastics [7]. These fish-derived products have significant applications in industries such as aquaculture, agriculture, food, cosmetics, biomedical, and pharmaceutical, offering potential economic and environmental benefits [51].

Biopolymers derived from fish waste (skin, scales, bones) offer a sustainable alternative to conventional plastics, with benefits including biodegradability and non-toxicity [52] [53]. Fish waste is rich in valuable compounds like collagen, chitin, and gelatin, which can be processed into high-value biopolymers for applications in medicine, agriculture, food packaging, and cosmetics (Fig. 2). The use of fish waste-derived biopolymers can contribute to waste valorization, reduce plastic pollution, and promote sustainable material development, supporting a circular economy. Researchers developed biodegradable bioplastics using sericin from silk cocoon waste and gelatin from fish waste, combined with nano-reinforced cellulose crystals [54]. The bioplastic material showed promising properties, including a tensile strength of 27.64 MPa and a degradation rate of 85% after 14 days in burial experiments [8]. This sustainable approach utilizes waste materials, reducing environmental pollution, and offers a potential alternative to traditional plastics for packaging and disposable applications. This review discusses such interesting and up to the minute applications of gelatin derived from fish biowaste [55].

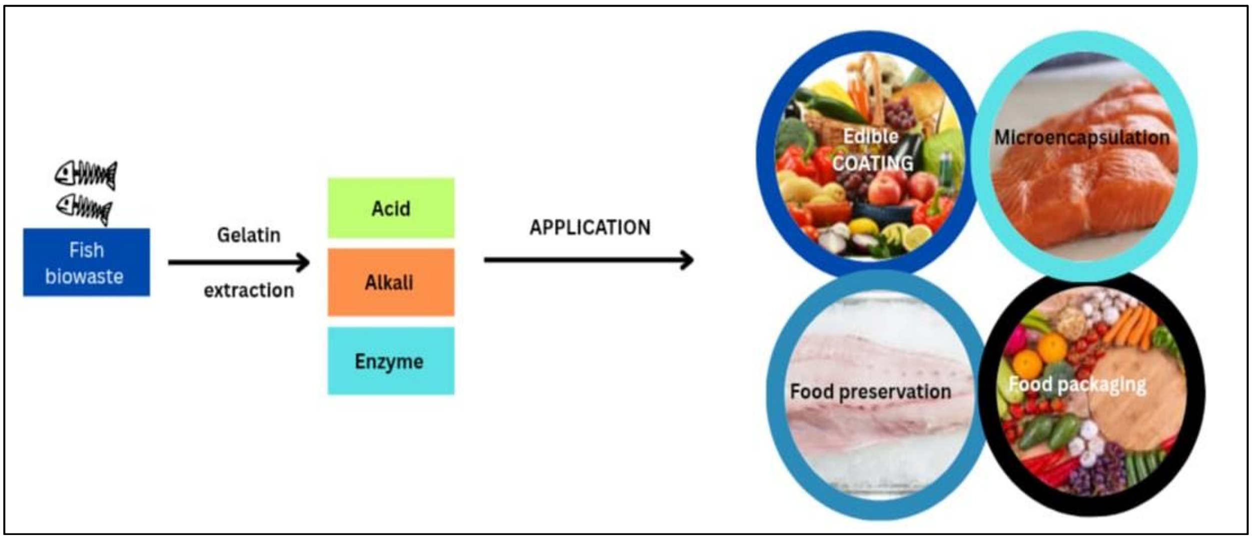

Fig 2 Gelatin Recovery from Fish Biowaste and its Applications

➢ *Fish Biowaste Derived Gelatin in Food Sector*

Fish waste, which constitutes a major portion of total fish biomass, contains collagen-rich components like skin, bones, and scales. These by-products can efficiently be converted into gelatin, offering a sustainable alternative to the mammalian sources for food applications [9][60]. Fish-derived gelatin displays desirable functional traits such as gelling, emulsifying, stabilizing, and thickening, making it suitable for a variety of food products including dairy, desserts, meats, and beverages[56]. Its broader acceptance across religious and cultural groups adds to its global usability (Fig. 3). The extraction process typically involves acid, alkaline, or enzymatic treatments, with enzymatic methods—particularly using pepsin—yielding higher quality gelatin [57]. Recent advancements such as ultrasound and high-pressure processing further enhance both yield and quality. Recovering gelatin from fish waste not only adds economic value but also addresses environmental concerns by minimizing pollution and aligning with circular economy goals through waste valorization[58] [59].

Fig 3 Fish Biowaste Derived Gelatin's Eminent Properties that Support Food Sector

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Fish processing residues such as skins, bones, and scales are valuable sources of collagen, which can be transformed into gelatin through hydrolysis [68]. The typical extraction process involves initial treatments—often using acidic or alkaline solutions—to eliminate fats and non-collagenous proteins, followed by heat-based extraction [67]. Among these sources, fish scales have been particularly effective for gelatin production, which is then utilized in edible films and encapsulation techniques [10]. Gelatin derived from fish skin and bones is recognized for being biodegradable, with good film-forming capacity, making it a potential replacement for mammalian gelatin. Applications include edible coatings, microencapsulation, and active packaging, benefiting from gelatin's antioxidant and antimicrobial qualities [11].

➢ *Food Packaging*

Traditional petroleum-based food packaging is harmful to the environment [66], prompting the development of biodegradable alternatives like chitosan (CH), gelatin (GE), and cellulose nanocrystals (CNCs). Novel packaging films were made from CH, GE (extracted for the first time from *Tenualosailisha* fish scales, and CNCs via solution casting [12]. Characterization techniques such as FTIR, XRD, TGA, UV-vis, and SEM confirmed the functional and structural integrity of the films. Incorporating CNCs enhanced mechanical strength, flexibility, and swelling while reducing solubility. Elongation at break improved from 48% to over 64%, and with CNC addition tensile strength increased from 12.24 to 13.93 N/mm². The films were highly transparent, stable, and biodegradable—showing 49–60% deformation in 7 days and 71–84% biodegradation in 21 days under natural soil. These properties make the films excellent candidates for sustainable food packaging applications [61].

Due to its excellent film-forming ability, affordability, biocompatibility, and biodegradability, fish gelatin is increasingly being used to create biodegradable films for active food packaging as an alternative to synthetic polymers and mammalian-derived gelatins [62]. It is processed easily using heat and mechanical force via extrusion methods. Plasticizers enhance its flexibility by increasing molecular mobility [64]. Gelatin films made through aqueous casting are tasteless, colorless, transparent, water-soluble, and more flexible than many other bio-based packaging materials [63]. Their melting point, close to human body temperature, also makes them suitable for edible film applications. Moreover, fish gelatin serves as a promising matrix for incorporating bioactive compounds with antioxidant and antimicrobial effects [69]. However, high hygroscopicity reduces their moisture barrier and mechanical strength, and they also have low oxygen permeability, which limits their performance in food packaging [11][65].

➢ *Edible Films and Encapsulation*

Fish scale-derived gelatin has been extensively employed in forming edible films and for encapsulation purposes [10]. Azmi et al. (2020) [10] studied Tilapia scale gelatin films with various plasticizers and observed that plasticizer type significantly influenced properties such as glass transition temperature, thermal stability, protein–plasticizer interactions, and film flexibility. Weng and Wu (2019) [13] improved the thermal and mechanical properties of these gelatin films through heat treatments at 100–120 °C, which promoted cross-linking between gelatin chains. This process shifted the bonding types from ionic and hydrogen to more stable hydrophobic and covalent interactions, enhancing water resistance [70]. Researchers demonstrated that chitosan–gelatin films could delay microbial growth on fish, supporting their potential use in food protection. Additionally, such coatings have been effective in preserving refrigerated rainbow trout and Pacific white shrimp by reducing spoilage and oxidation [14]. Despite their benefits, potential toxicological risks during handling or consumption remain to be fully assessed [15].

The use of fish waste, specifically gilthead seabream by-catch, was explored to produce biodegradable packaging by extracting fish protein concentrate (FPC) and combining it with gelatin [71]. Using the solvent casting method, films were developed and evaluated for water vapor permeability, mechanical strength, wettability, and color. Adding FPC reduced the contact angle but maintained hydrophobicity, slightly lowered tensile strength, and improved flexibility[72] [73]. Both FPC–gelatin and pure gelatin films were transparent and colorless, making them suitable for food packaging. This approach supports circular economy goals by reducing reliance on petroleum-based plastics [16].

Biodegradable edible films were developed from cassava starch, fish gelatin (from waste), and cinnamon essential oil nanoemulsion (CEON) to extend fish fillet shelf life. The optimal formulation (SGCEON3) combined 5% starch with a 1:3 ratio of gelatin and 10% CEON, showing strong antioxidant and antimicrobial properties that preserved fish fillets for up to 10 days. The films demonstrated improved thickness, tensile strength, flexibility, and thermal stability [74]. Analytical results confirmed compatibility among components and a sustained release of essential oil, making SGCEON3 an effective antimicrobial packaging alternative [17].

➢ *Food Coating and Preservation*

Gelatin derived from fish exhibits outstanding film-forming characteristics, making it ideal for creating biodegradable packaging materials [75]. These films are generally transparent, tasteless, water-soluble, and colorless, with greater flexibility than many other biopolymer-based films [10][77]. Furthermore, since the melting point of gelatin is close to human body temperature, it is well-suited for edible film applications [13][76]. To enhance the performance of fish gelatin films, several modifications have been explored:

- *Plasticizers:* Incorporation of different types of plasticizers influences various properties, such as glass transition temperature, chemical interactions between gelatin and plasticizer, thermal degradation, strength, and flexibility [10][79].

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- *Heat treatments:* Heating gelatin films at temperatures between 100°C and 120°C has been shown to improve their mechanical and thermal properties by fostering cross-linking between gelatin chains. This modification results in a shift from weaker ionic and hydrogen bonds to stronger hydrophobic and covalent interactions, thereby increasing water resistance [13][80].

- *Chitosan–Gelatin Blends:* Combining chitosan with gelatin to form composite films can effectively slow down or even prevent microbial growth on fish, indicating their usefulness in preserving seafood [14]. These blended films have also demonstrated success in extending the shelf life of refrigerated products like Pacific white shrimp and rainbow trout [14][78].

II. FISH BIOWASTE DERIVED GELATIN IN PHARMACEUTICALS AND DRUG DELIVERY

Several reviews have explored different aspects of fish gelatin, such as its preparation, properties, modifications, and various applications [81]. While its use in food packaging has been extensively discussed, other potential applications are often overlooked or only addressed in conjunction with collagen. This review offers a comprehensive and focused overview specifically on fish gelatin and its hydrolysates, supported by recent research [83]. It highlights biological activities and a wide range of biomedical applications, including wound dressing and healing, gene therapy, tissue engineering, implants, and bone substitutes [38]. Additionally, it details pharmaceutical uses such as capsule production, coating of microparticles and oils, tablet coatings, emulsion stabilization, and drug delivery systems including microspheres, nanospheres, scaffolds, microneedles and hydrogels [18] [82].

Fish gelatin is a promising alternative for capsule production due to its film-forming properties and suitability for encapsulating marine-based supplements [39]. While its low gelling temperature—linked to reduced proline and hydroxyproline content—poses a challenge, this can be mitigated by crosslinking with transglutaminase. Studies have shown that fish gelatin, when combined with glycerol and water, offers thermomechanical properties comparable to bovine and porcine gelatin [84]. A 20% solution of tuna skin gelatin has been found optimal for hard capsule formation, meeting key pharmaceutical standards. Fish gelatin capsules are particularly effective for delivering active ingredients like EPA-rich fish oil, spirulina, and algae extracts [85]. Coacervation is an effective coating technique used to mask unpleasant tastes or odors in drug formulations, particularly for insoluble particles. It involves phase separation of film-forming polymers like gelatin around microparticles in the presence of a coacervating agent, followed by crosslinking to solidify the coating. Fish gelatin, which dissolves at lower temperatures (5–10°C) is especially advantageous for thermolabile drugs, offering improved protection against oxygen and moisture. However, this method is unsuitable for ion-exchange resins due to their charge properties. Key factors like mixing speed, coacervant addition rate, and collection method influence coating quality and dispersibility [19].

Gelatin, a product of partially denatured collagen, is widely used across multiple industries [86] [88]. Most of the gelatin used worldwide is derived from mammalian sources, particularly porcine and bovine. However, concerns related to health, religion, and dietary restrictions have driven interest in alternative sources, such as marine-derived gelatin[87]. Fish gelatin, although less robust and characterized by lower melting and gelling points compared to its mammalian counterparts, has shown promise through various modifications aimed at enhancing its rheological and functional properties [40]. This review explores the growing range of innovative applications for fish gelatin, particularly in the food sector, pharmaceuticals, and therapeutic contexts [101]. Notably, fish gelatin can serve as an effective carrier in drug delivery systems due to its adaptability. It can be formulated into different delivery structures, including microparticles, nanoparticles, fibers, and hydrogels [41][89]. Additionally, the review highlights the potential of fish gelatin in other pharmaceutical applications such as tissue repair, antioxidant therapy, and treatments for hypertension and cancer [18]. Gelatin is widely utilized as an excipient in numerous pharmaceutical dosage forms [90]. Its applications include the formulation of hard and soft capsule shells, tablets, suspensions, emulsions, and injectable products such as plasma expanders. This versatility makes gelatin a valuable natural polymer in the pharmaceutical industry, as well as in food and cosmetic applications [20].

- *Fish Biowaste Derived Gelatin in Cosmetics and Skincare*

In the cosmetic industry, the growing consumer demand for sustainability and eco-friendly solutions has presented two key challenges. The first involves incorporating natural compounds into products to meet consumer expectations for greener and more natural formulations, along with the necessary adjustments to production processes to support this change [91]. The second, and more transformative challenge for the industry, is the need to identify new, sustainable sources of bioactive natural compounds (Table 1). In response to this need—and as companies strive to expand the boundaries of knowledge in their search for sustainable ingredients—byproducts have emerged as a promising solution [21] [92].

The cosmetic industry has been motivated to adopt sustainable practices to address its significant carbon footprint and the intensive extraction of raw materials. Embracing the principles of the circular economy and bioeconomy has been identified as a viable solution [94]. Within these frameworks, integrating byproducts into the cosmetics production process—whether as bioactive ingredients or structural components—emerges as a natural progression [93]. This session aims to offer a comprehensive overview of how bioactive byproducts are used in cosmetics, highlighting not only their potential biological benefits but also the regulatory, societal, and economic implications of their inclusion and the ways in which they can support the industry's sustainability goals [22].

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Table 1 Fishery Discards Derived Byproducts' Significance in Cosmetics Sector [21] [22] [23]

Criteria	Justifications
Industry Importance	Major contributor to global economy and lifestyle influence
Annual Revenue	Generates billions of dollars worldwide
Consumer Influence	Shapes perceptions of beauty, trends, and cultural standards
Innovation	Use of food co-/by-products in skincare, hair care and packaging
Sustainability Goal	Enhancing well-being while respecting Boundaries
Ingredients Source	Nutrients and antioxidants from organic waste
Challenges	Consumer acceptance, shelf life, and safety concerns
Regulatory Needs	Clear labelling requirements and good Manufacturing practices required

Scanning electron microscope (SEM) supports the cosmetological extraction of gelatin, enabling investigation of its structural morphology, in terms of the occurrence and assemblage of fibrils. The range of gelatin/collagen denaturation, its surface area and microstructure could be keenly studied by SEM. Such examinations give ideas regarding the probable applications of waste derived gelatin/collagen in industries [95]. Evidences show that Nile tilapia and channel catfish skin-derived gelatin was built with a dense fibril structure, where porosity was significant for its ready use in cosmetic applications as hydrating agents [23].

- *Fish Biowaste Derived Gelatin in Biomedical Sector*

Gelatin has recently gained considerable interest due to its wide availability and beneficial bioactive properties [96]. Fish skin, which is rich in collagen, serves as a valuable source for gelatin production, adding significant worth to this by-product [34]. Numerous studies have explored the extraction of gelatin from various fish species, including warm-water fish like catfish, Nile perch, shark, tuna, megrim, and tilapia, as well as cold-water fish such as hake, cod, Alaska Pollock, and salmon [100]. Extraction yields typically range from 2% to 20%, depending on the methods used. This section highlights different techniques for obtaining gelatin peptides from fish skin and discusses how processing affects their composition and functionality [35]. It also outlines the wide range of bioactivities exhibited by these peptides, such as antioxidant, antimicrobial, anti-inflammatory, and anticancer effects. These findings suggest strong potential for using fish skin-derived gelatin peptides in pharmaceuticals, functional foods, and nutraceuticals [24] [37].

Researchers explored the application of bioresorbable phosphate-based glass fibres (PGFs) coated with gelatin derived from tilapia fish scales (fish scale gelatin, FSG) for potential use in wound healing. Analysis of FSG indicated a high protein content of 89.4%. Furthermore, its bloom gel strength, viscosity, SDS-PAGE molecular profile, and functional group composition were found to closely resemble those of bovine gelatin [25]. Gelatin has a composition that is closely related to its precursor, collagen. It is particularly rich in specific amino acids, including glycine (approximately 21%), proline (12%), and hydroxyproline (12%). Collagen is considered one of the most promising natural biomaterials for constructing scaffolds in tissue engineering [36]. This is due to its important role in supporting cell adhesion and differentiation, which are essential for cell regeneration [27].Synthetic polymer-based scaffolds are widely used in cartilage repair. However, gelatin obtained from various marine sources presents several advantages [99]. These include better biosafety, higher biocompatibility, and reduced antigenicity compared to synthetic materials [26].

A biocompatible polymeric bio-scaffold (BPBS) composed of collagen (CL), gelatin (GL), and squid ink (SI) was developed for wound healing applications. Prepared from fishbone collagen, fish skin gelatin, and squid ink, the BPBS showed excellent biocompatibility, physicochemical stability, and antimicrobial activity, with inhibition zones of 4.57 ± 0.30 mm against *E. coli* and 4.74 ± 0.15 mm against *Staphylococcus aureus*. Both *in vitro* and *in vivo* studies confirmed that the inclusion of SI significantly enhanced wound healing efficacy in repairing incised skin tissue defects [28].

Tilapia waste has been effectively utilized in various fields, including biomedical applications like wound dressings, hydroxyapatite synthesis, gelatin extraction [98].Brazilian doctors pioneered the use of sterile tilapia skin to treat burn patients, a method that attracted global interest due to its effectiveness and cost-efficiency. The treatment not only reduced the need for pain medication but also accelerated the healing process by a few days. This healing potential is attributed to the high collagen content in tilapia skin, which stimulates fibroblast growth factor and supports tissue regeneration [29][97].

Diets high in fish products have been linked to improved survival rates in cancer patients, with various studies supporting the connection between fish consumption and cancer prevention.For instance, a study demonstrated the antiproliferative effects of fish protein hydrolysates (FPH) on two human breast cancer cell lines in vitro [30]. Additionally, in mice with Lewis lung carcinoma, omega-3-rich fish oil diets reduced tumor growth and metastatic mass, while also enhancing the efficacy of chemotherapy drugs [31]. These articles revealed that collagen and gelatin based nanotechnology holds great potential due to ongoing scientific advancements in the field. Nano biomaterials, offer improved wound site penetration and enhanced cell interaction because of its high surface-area-to-volume ratio [32]. The fish collagen (gelatin) is more used in wound healing materials that combine antimicrobial, antioxidant,

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and UV-blocking properties. UV protection is especially important, as newly formed tissue around wounds is delicate and vulnerable to damage from high-energy radiation, which can also generate reactive oxygen species that exacerbate inflammation. The UV-shielding ability of materials is closely linked to their structural and chemical makeup, with ZnAlTi layered double hydroxides being a quite popular example [33].

III. CONCLUSION

Aquaculture sector represents a crucial part of our economy. Fishery discards' management is indeed a complicated issue as they are perishable. Contrarily, recovery of bioactive materials such as collagen and gelatin from such discards (biowastes) stimulates the research for possible sustainable industrial solutions. This review article summarizes the so far exercised sustainable strategies researched to valorise the fish biowaste for gelatin recovery. This would provoke the enthusiasts and signify the importance of bioactive peptides such as gelatins and collagens derived from fish biowastes and their multifarious promising industrial applications. Thus, fishery discards that were of zero economic value, are now scientifically exploited for bioactive molecules. Still, difficulties associated with the practical and economic side of such green strategies remains unanswered while probing for advancements to justify the criticisms.

- *Conflict of Interest*

Authors declare no conflict of interest.

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