Innovative Romanian Food Biotechnology
https://www.gup.ugal.ro/ugaljournals/index.php/IFRB Vol. 29, 2026
2026 by Galaţi University Press
Received May /Accepted July 2026

REVIEW ARTICLE

BLUE BIOTECHNOLOGY: EXTRACTION OF BIOMATERIALS OF MARINE FAUNA

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Abstract: Marine biomaterials have gained significant relevance in biotechnology due to their biocompatibility, biodegradability, and abundance. This research addresses the extraction and application of high-value compounds from marine fauna as alternatives to synthetic materials. The first section focuses on polysaccharides and fibrous proteins: chitin and chitosan from crustacean exoskeletons, noted for their antimicrobial properties and drug-delivery applications; and collagen, gelatin, and elastin, derived from fish tissues and scales, essential for tissue engineering and cosmetics. The second section examines marine biominerals, such as hydroxyapatite and calcium carbonate from seashells and fish bones, which serve as scaffolds for bone regeneration and cell growth. This study highlights a multidisciplinary approach integrating chemistry, biology, and nanotechnology to optimize the extraction and modification of these biopolymers and minerals. The findings position marine-derived materials as fundamental pillars for future developments in regenerative medicine and sustainable industrial applications.

Keywords: *Marine biomaterials, polysaccharides, fibrous proteins, marine minerals, blue biotechnology.*

2026 by Galaţi University Press
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Introduction

Marine ecosystems are home to an impressive variety of life forms, making them the most biodiverse environments on the planet. This biological richness makes them an essential source of natural compounds, especially those derived from algae, microalgae, and invertebrates. Covering more than 70% of the Earth's surface, the oceans represent the largest reserve of biological, genetic, and biochemical diversity on the planet. The demands of survival in this environment have favored the development of unique adaptations that give rise to a vast range of bioactive compounds in the marine environment (De Ita Zárate, 2021).

Marine ecosystems provide access to natural, abundant, and low-cost biomaterials that differ significantly in structure, composition, and biological functions from those derived from terrestrial species. These resources include polysaccharides, natural proteins, fatty acids, and minerals, which have shown great potential in the creation, improvement, and stabilization of multifunctional nano, bio, and microsystems (Wang *et al.,*2023).

Research on biomaterials has advanced steadily in recent years, especially with the integration of biologically active compounds. These materials are no longer simple implantable devices. Biomaterials are not only designed to replace diminished or lost functions, but have evolved into complex, multifunctional platforms that actively interact with the recipient organism, stimulating its natural capacity for regeneration. These compounds have also had a rapid impact on drug technologies and their effect on modern medical treatments (Osorio-Delgado *et al.,* 2017).

Biomaterials are fundamental to contemporary life, to the point that it would be difficult to imagine modern medicine, pharmacies, and cosmetics without them (Marin *et al.,* 2020).

Among the different types of biomaterials are those of marine origin, which are defined as any material of biological origin obtained from the marine environment (oceans, seas, coasts) and which can be used in multiple applications. Marine biomaterials stand out for their biocompatibility and biodegradability, making them ideal candidates for applications such as controlled drug delivery, tissue development, and other medical innovations (Wang *et al*., 2024).

Marine biomaterials represent a valuable source of natural compounds with applications in medicine, cosmetics, pharmacology, and biotechnology. For example, chitin and chitosan, derived from the exoskeletons of crustaceans, have antimicrobial and healing properties and are

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Received May /Accepted July 2026

used in the manufacture of dressings, drug delivery systems, and water purification filters (Mármol *et al*., 2011; Romero–Serrano and Pereira, 2020).

Chondroitin sulfate, extracted from fish cartilage, is essential in the treatment of joint diseases such as osteoarthritis, as it contributes to cartilage regeneration and reduces inflammation (Peniche *et al*., 2001; Schiraldi *et al*., 2010; Demirci *et al*., 2021).

Marine collagen (type I collagen), obtained from fish skin and scales, is notable for its high biocompatibility and is used in regenerative therapies, anti-aging products, and nutritional supplements. Gelatin, derived from collagen, is used in the food, pharmaceutical, and cosmetic industries for its ability to form gels, encapsulate compounds, and improve product texture. Elastin, present in marine connective tissues, provides elasticity and firmness to the skin and is key in cosmetic formulations to combat ageing (Chilkoti *et al*., 2006; Huang *et al*., 2023; Gu *et al*., 2019).

Hydroxyapatite extracted from fish represents a sustainable and highly functional alternative in the development of biomaterials. This compound is found in fish scales, bones, and spines, and can be obtained through thermal processes or chemical treatments. These physicochemical procedures achieve a crystalline structure similar to that of human bone tissue. Hydroxyapatite is the main mineral component of bone and is widely used in implants and prosthetic coatings due to its ability to integrate with bone tissue without causing rejection. This material is also widely used in catalysis as a catalytic support, showing excellent applications in environmental chemistry (Loo *et al*., 2010; Cursaru *et al*., 2022).

Calcium carbonate, on the other hand, is used in bone regeneration, cell scaffold manufacturing, and as a support in cell cultures due to its porosity and biodegradability (Fadia *et al*., 2021).

Hydroxyapatite and marine calcium carbonate promote osseointegration and stimulate osteocellular proliferation, making them key in regenerative therapies and tissue engineering development. In addition, their natural origin and low cost make them sustainable alternatives for clinical applications. In dentistry, they are used in bone fillings and dental coatings. They are also being researched as vehicles for transporting bioactive molecules. Their versatility is driving advances in personalized medicine and less invasive treatments (Uskoković and Uskoković, 2010; Loo *et al*., 2010).

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The main properties of marine biomaterials are that they are biodegradable, renewable, and promote a circular economy by valorizing fishing waste. In addition, their extraction and use encourage sustainable development and innovation in key sectors of the economy. Research into marine biomaterials opens up new possibilities for personalized medicine, tissue engineering, and the creation of smart materials that respond to the increasingly complex demands of modern industry. The versatility of these materials and their natural origin make them strategic allies in addressing challenges in health, the environment, and converging technologies.

Biomaterials are currently used in skin substitutes, bioelectrodes, in vitro and in vivo diagnostic tests, controlled drug delivery systems, and in the functional development of tissues and regenerative medicine, among many other innovative applications (Wong-Hernández *et al*., 2019; Ratner, 2013).

This review presents a detailed analysis of recent advances in biomaterials derived from marine fauna, which represent a sustainable alternative for various industrial sectors. It examines compounds such as chitin, collagen, and hydroxyapatite derived from mollusks, crustaceans, and fish, highlighting their biocompatibility and low toxicity. The objective of this study is to evaluate the potential of marine fauna as a sustainable source of high-value biomaterials, analyzing biotechnological extraction processes and their innovative applications in fields such as medicine, pharmacology, and tissue engineering. In this way, the aim is to promote the circular economy by valorizing marine byproducts without compromising species conservation.

Materials and Methods

Search strategy

The methodology of this review was framed under the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Moher *et al.*, 2015). The selection process was systematically executed through the four essential phases: identification of records, screening, eligibility evaluation, and the final inclusion of studies. Pubmed, Web of Science, The Lens.org and Google Scholar database search phrases for the year 1990 through 2025 were used to identify every relevant article. Lens.org was selected for its comprehensive integration of scholarly literature and patent data, providing a broader view of both academic research and technological innovations in marine biotechnology. Google Scholar was utilized to ensure

maximum coverage of grey literature and recent pre-prints, ensuring that the latest advances in blue biotechnology were captured.

The following strings were used for article searching:

- Biopolymers and Proteins: (“Marine biomaterials” OR “Blue biotechnology”) AND (“Chitin” OR “Chitosan” OR “Collagen” OR “Gelatin” OR “Elastin”) AND (“Extraction” OR “Characterization” OR “Marine fauna”).
- Minerals and Circular Economy: (“Marine waste” OR “Fish by-products” OR “Fish scales” OR “Fish bone”) AND (“Hydroxyapatite” OR “Calcium carbonate”) AND (“Circular economy” OR “Sustainable development”).

Inclusion and exclusion criteria

Studies were included if they were written in English or Spanish, focused on the chemical extraction, physical characterization, or biotechnological application of biomaterials derived from marine fauna (crustaceans, mollusks, and fish), and provided primary research data or comprehensive state-of-the-art syntheses. To ensure a balanced and updated review, a selection criterion of 8 to 12 key papers per biomaterial category was applied, primarily prioritizing publications from the last 5 to 10 years. Foundational studies were included as necessary exceptions to provide biochemical context. Additionally, relevant previous publications by the authors were incorporated to ensure continuity in the established research lines regarding marine waste valorization. Publications were excluded if they focused on terrestrial-sourced biomaterials, purely synthetic polymers, or consisted of non-scientific outputs such as news reports or commercial brochures.

Screening and duplicate removal

A total of 4069 records were initially identified (24 from Pubmed, 160 from Web of Science 485 from Lens.org and 3,400 from Google Scholar). After removing duplicates and non-peer-reviewed records, 576 articles were screened by title and abstract. During the eligibility assessment, 492 papers were excluded for not meeting the specific criteria for marine fauna extraction or for being outside the prioritized timeframe. Finally, 84 articles were included for

qualitative synthesis. The complete selection process, following the identification and filtration criteria, is illustrated in the PRISMA flow diagram (Figure 1).

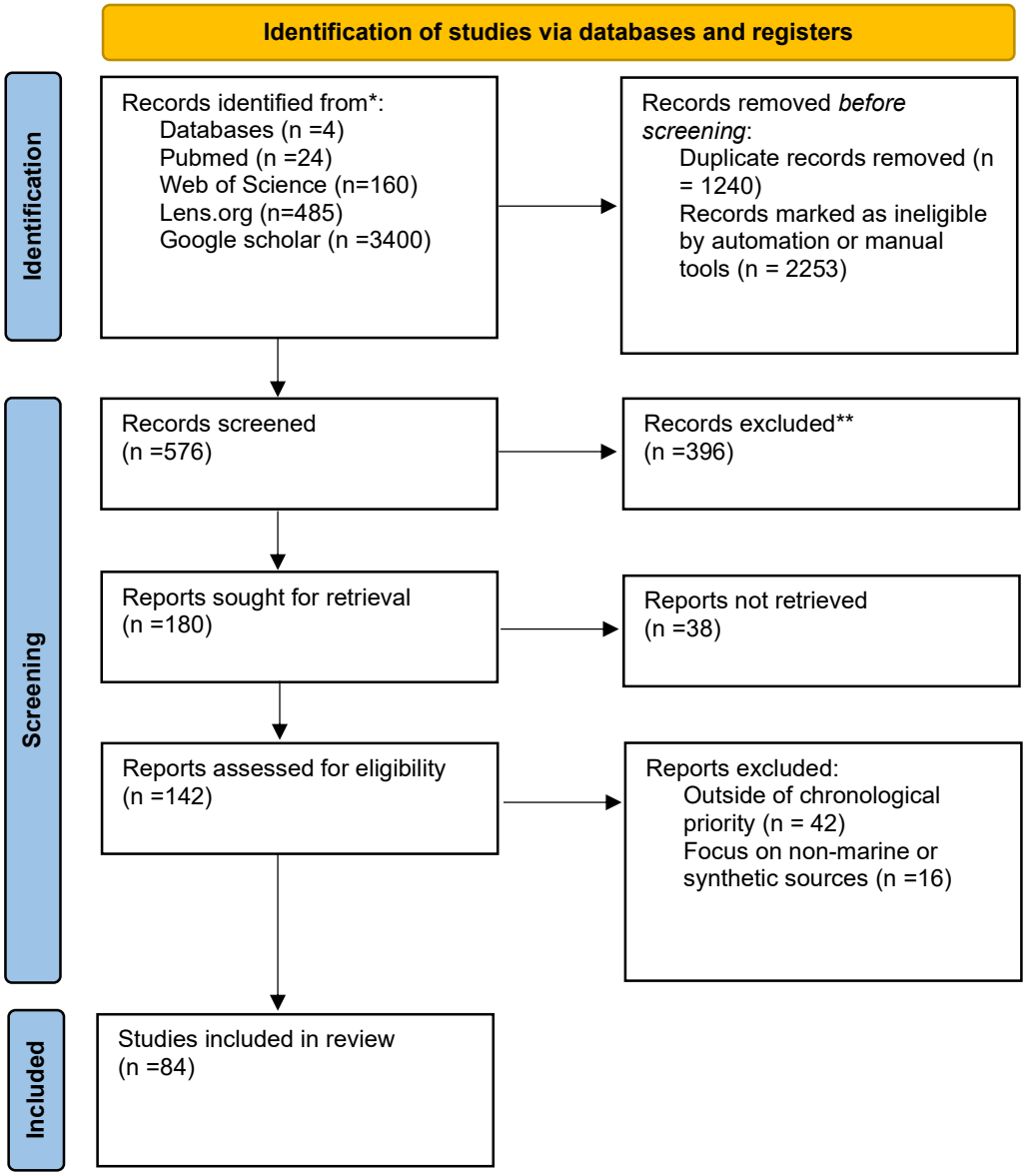


Figure 1. PRISMA flow diagram of the systematic literature search and selection process for marine-derived biomaterials and circular economy applications.

Results and discussion

Polysaccharides and fibrous proteins

A. Chitin and chitosan

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Chitin has a chemical structure composed of N-acetyl-D-glucosamine (GlcNAc) that interacts with itself through β (1→4) bonds. This compound is classified as a biopolymer with characteristics of biocompatibility, biodegradability, absence of toxicity, and antimicrobial activity (Jayakumar *et al*., 2010). It is found endogenously in the exoskeleton of arthropods such as crabs, shrimp, lobsters, and other marine organisms (Rinaudo, 2006).

The water insolubility of chitin limits its applications due to its molecular structure. However, through chemical treatments, it is possible to transform chitin into chitosan by performing partial or total deacetylation, which generates a linear configuration of D-glucosamine (GlcN) and GlcNAc, allowing solubility in aqueous solutions with a pH lower than 6.5 due to the protonation of the amino groups (-NH2) (Kumar, 2000). In this process, molecular weight is a key parameter for determining the degree of deacetylation, which is a key factor in the quality of chitosan.

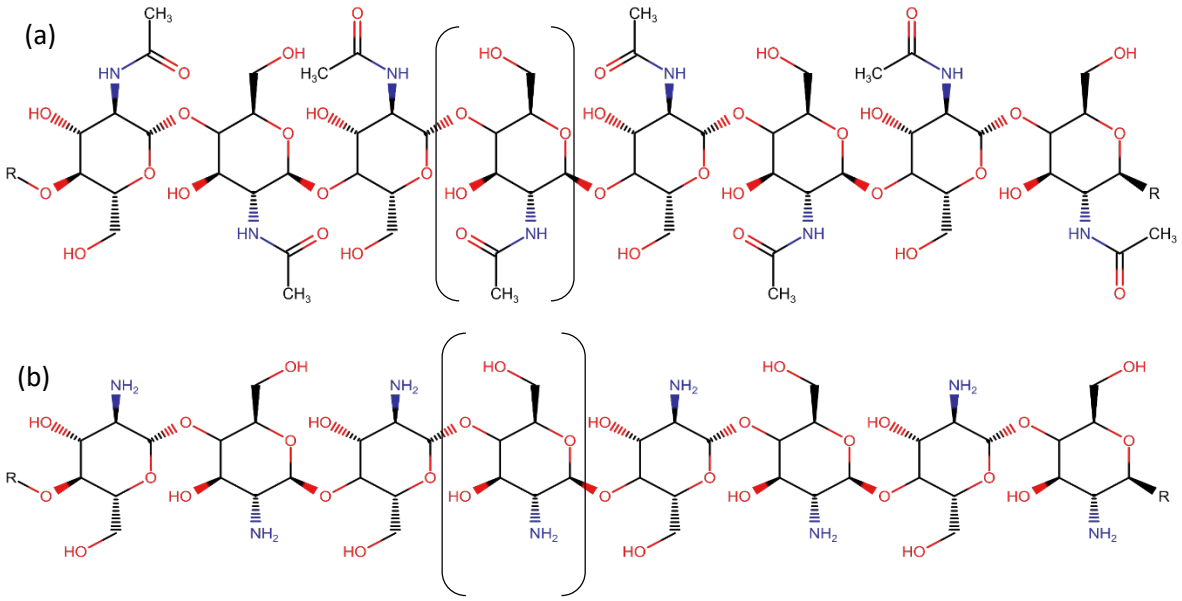


Figure 2. (a) Polymeric configuration (Fisher projection) of chitin composed of GlcNAc monomers, R being GlcNAc. (b) Polymeric configuration (Fisher projection) of chitosan composed of GlcN, R being GlcN. O: oxygen, N: nitrogen, C: carbon, H: hydrogen.

Crustacean waste is a sustainable source of chitin that must be processed by alkaline deproteinization with 4% sodium hydroxide in a 1:10 solid: solution ratio at 75°C for 2 h with constant stirring. Demineralization is carried out with 2 N hydrochloric acid in a 1:10 solid-liquid ratio at room temperature for 90 min. Sometimes, depigmentation of the biomaterial is also applied to improve the appearance of the chitin (Synowiecki and Al-Khateeb, 2003).

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Chitosan is obtained by subjecting chitin to a 40-50% sodium hydroxide solution in a solid: liquid ratio (1:10) at moderate temperatures (80-120°C) for 2 h, removing the acetyl groups (Novikov *et al*., 2022).

Centeno-Bordones *et al*. (2024) demonstrated that it is possible to obtain satisfactory results by changing the order of the unit processes: demineralization, then deproteinization, and finally deacetylation. Other authors have obtained chitosan by applying enzymes such as chitin deacetylase (Tsigos *et al*., 2000).

Chitosan's ability to form gels and bioadhesive films has led to its use in the production of healing membranes and controlled drug delivery systems (Dutta *et al*., 2004). The antimicrobial property of chitosan is exploited in the food industry as a natural preservative by means of an edible coating for fruits, vegetables, and meats (Shahidi *et al*., 1999). In the case of water treatment, both biopolymers (chitin and chitosan) have the property of capturing dyes and heavy metals. This reactivity of chitosan is due to its amino and acetyl groups, which are even capable of forming chelates with various metal ions (Crini and Badot, 2007). Finally, in agriculture, chitosan stimulates plant growth and induces resistance against fungi, bacteria, and viruses (Hadrami *et al*., 2010).

B. Chondroitin sulfate

It is a sulfated glycosaminoglycan (GAG) located in the cellular matrix of cartilage, connective tissue, skin, blood vessels, and the cornea. It consists of repeating disaccharides composed of D-glucuronic acid (GlcA) and N-GlcNAc with sulfonate groups on one or both pyranoses at the C4 or C6 positions (Awofiranye *et al*., 2022). It forms β-(1→3) bonds from GlcA and GlcNAc, and β-(1→4) bonds between GlcNAc and GlcA, forming linear polymer chains (Prydz, 2015). The sulphate group confers high activity with extracellular matrix proteins, growth factors, and interaction with divalent cations such as calcium (Vasconcelos, 2017).

This polysaccharide has been isolated from various marine sources: shark cartilage, rays, bony fish, and invertebrate organisms such as ascidians and echinoderms (Higashi *et al*., 2015). However, the cartilage of *Prionace glauca* or *Squalus acanthias* sharks is an important source for the extraction of chondroitin sulphate. This compound is predominantly found in hyaline cartilage, associated with type II collagen (Pan *et al*., 2023).

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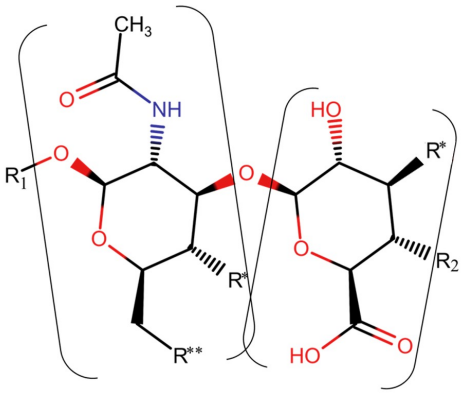


Figure 3. Chemical structure (Fisher projection) of chondroitin sulfate, R1 being GlcA, R2 is GlcA, R* could be a sulfate or hydroxyl group and R** would be a carboxyl or sulfate group (R* and R** could both be with sulfate groups, although these are atypical cases) [12]. O: oxygen, N: nitrogen, C: carbon, H: hydrogen.

The extraction process begins with washing, degreasing, and drying the cartilage tissue, followed by proteolytic digestion with papain enzymes for 12-24 hours at 55-60°C at a pH of 6, which will release the GAGs from the protein matrix (Talmoudi *et al*., 2020). Once digestion is complete, 70-80% ethanol is added to precipitate it, after which it is purified in an ion exchange resin column such as DEAE-sephacel, flowing with 2M NaCl gradients (Carvalho *et al*., 2024). Finally, dialysis is performed to remove the salts present, and freeze-drying is used to dry the product. The quality and degree of sulfation are related to the marine species, the tissue of origin, and the environmental conditions (Urbi *et al*., 2022).

Chondroitin sulfate is used in regenerative medicine, tissue engineering, cosmetics, and as a nutraceutical supplement. Its best-known use is in the treatment of osteoarthritis, due to its anti-inflammatory and chondroprotective properties and its ability to improve joint lubrication (Zhu *et al*., 2024). It has also been proposed for cartilage regeneration, as a component of hydrogels, scaffolds, and controlled drug delivery systems (Rajesh *et al*., 2025).

C. Collagen and gelatin

Collagen and gelatin have become commercially profitable products (Silva *et al*., 2014). Both chemical species share a biosynthetic origin, but differ in molecular structure, function, and extraction methods. Collagen is a fibrous biopolymer (sometimes glycoprotein) formed (in simplified terms) by monomers of glycine (Gly, up to 33.5%), proline (Pro, 10-12%), and hydroxyproline (Hyp, 9-10%). The variability between the amino acid monomers of collagen makes it a complex system, forming up to 29 different combinations. Type 1 collagen is the most

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abundant in connective tissues and the most extracted from marine sources such as the skin, bones, scales, and fins of bony fish; cephalopods, sharks, and rays (Jafari *et al*., 2020).

The molecular structure can be simplified into Gly-X-Y triplets, where, as a general rule, the first amino acid in the triplet is Gly (Shoulders and Raines, 2009) and where X and Y are Pro and Hyp respectively (in 10.5% of cases, the majority compared to the other combinations), but other amino acids such as alanine (~10%), arginine, glutamine, lysine, leucine, and serine are also evident. Finally, the heteropolymer establishes a helical configuration, forming fibers and fibrils through hydrogen bonds between the chains that stabilize the biomaterial (Ricard-Blum, 2010).

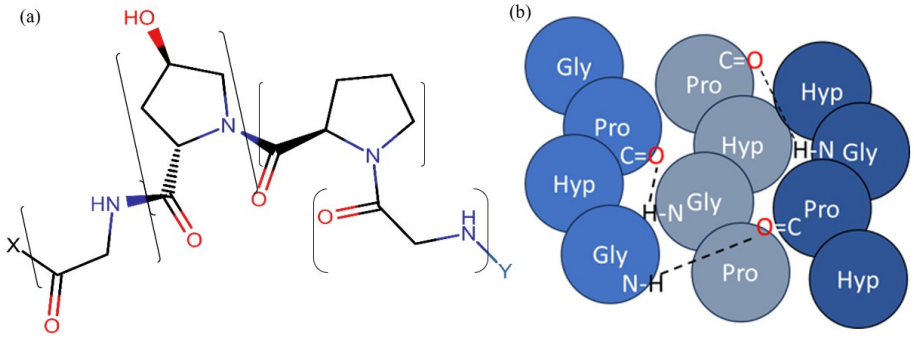


Figure 4. (a) Molecular structure (Fisher projection) of collagen, triplet Gly-Pro-Hyp-Gly. X and Y refer to Pro and Hyp, with Gly repeated every 3 monomeric units (X and Y can also be other canonical amino acids). (b) Interaction between collagen helices by means of hydrogen bonds. O: oxygen, N: nitrogen, H: hydrogen.

Meanwhile, gelatin is a product of the partial hydrolysis of native collagen. It breaks down the triple helix configuration to form a linear and disorganized polypeptide, obtaining a low gelation point in aqueous solutions (Gudmundsson and Hafsteinsson, 2006).

To obtain collagen, alkaline hydrolysis (NaOH 0.1 M, 24 h, 4°C) must first be performed to remove unwanted proteins and pigments. This is followed by extraction with 0.5 Molar acetic acid for 48 hours at 4°C in a solid: liquid ratio (1:30). Next, 2.5 M NaCl is added to precipitate the collagen, and finally, it is centrifuged (Nagai and Suzuki 2000). There are other methods that use pepsin (0.1% w/w) to maintain the helical configuration during acid extraction (Muyonga *et al*., 2003).

Gelatin requires additional thermal processes to break the hydrogen bonds responsible for the triple helix of collagen. To obtain type A gelatin, which comes from fish skin due to its low degree of cross-linking, acetic acid or citric acid between 0.05 and 0.5 M is used for 24 hours at

4-20°C (Ahmad and Benjakul, 2011). For type B gelatin, alkaline treatments are applied to bones or scales, using sodium hydroxide in concentrations of 0.1 to 0.2 M for periods of 1 to 3 days. This process attacks the covalent cross-links of collagen with other cellular components (such as lysine and hydroxylysine) (Venupriya *et al*., 2022). After chemical treatment, controlled thermal hydrolysis is carried out at 40 to 60°C for 24 hours, with a material: water ratio of 1:5, and filtered to remove sol-ids. It is then clarified by centrifugation or filter press, dried by evaporation or freeze-drying, and finally pulverized (Karim and Bhat, 2009). Table 1 summarizes the differences between gelatins A and B:

Table 1. Differences between the types of gelatin supported by Karim and Bhat (2009); and Schrieber and Gareis (2007).

Characteristics	Gelatin	
	Type A	Type B
Net load	Predominantly positive	Predominantly negative
Isoelectric point	7–9	4.7–5.2
State of deamidation	Minor (retains more amide groups, -$CONH_2$)	Major (more conversion to -COO^- y NH_4^+)
Functional groups	Fewer carboxyl groups (-COOH)	Greater number of carboxyl groups (-COOH)
Solubility	partially soluble at neutral pH	Best at low pH (acidic)
Applications	Food	pharmaceutical and biomedical

Collagen has applications in tissue engineering, such as scaffolding for bone and skin regeneration. It is also used as a membrane for wound healing and biocompatible coatings for medical implants (Vijayalekha *et al*., 2023). It is used in the cosmetics industry in a hydrolyzed form for emulsified products in dermatological treatments (Tong *et al.*, 2025). Gelatin is used in the food industry as a gelling agent, stabilizer, thickener, and water retainer in products such as desserts, yogurts, and processed meats. In the pharmaceutical industry, gelatin is used to make hard and soft capsules, tablets, suppositories, and matrices for controlled drug release. In the biomedical field, this bio-material has gained relevance in tissue engineering as a basis for the manufacture of three-dimensional scaffolds (Karim *et al*., 2019).

D. Elastin

2026 by Galaţi University Press Received May /Accepted July 2026

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Elastin is a structural protein, insoluble in water, which forms an essential part of the extracellular matrix, conferring elasticity. It is composed of valine (Val), alanine (Ala), glycine (Gly), proline (Pro), and desmosine (Des) (the latter being the site where four elastin chains cross through the condensation of three alisines with a lysine). Elastin is organized in an amorphous network, less orderly than collagen and characterized by its elasticity (Vrhovski and Weiss, 1998). Its tensile strength and thermal stability make it an important material for biomedical applications (Almine *et al*., 2010).

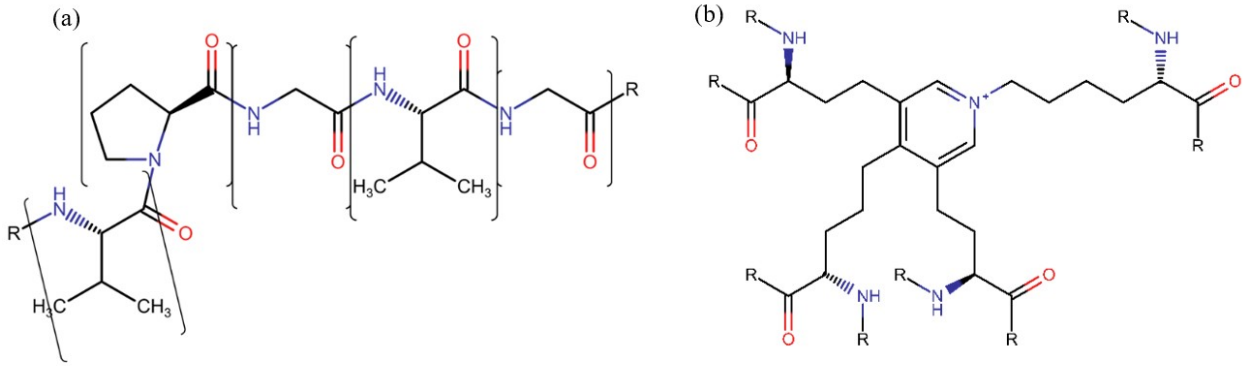


Figure 5. (a) Configuration (Fisher projection) of a common elastin chain Val-Pro-Gly-Val-Gly. Ala is regularly located in other common sequences such as Ala-Pro-Gly-Val-Gly-Val. (b) structure (Fisher projection) of Des (Schräder *et al*., 2015). R would be the continuation of the peptide chain. O: oxygen, N: nitrogen, C: carbon, H: hydrogen.

This biomaterial is obtained from mammalian sources, however, marine sources such as sharks and teleost fish skin have been explored (Ehrlich, 2014), which allows for its valorization within the concept of the circular economy.

Elastin extraction begins with the separation of dehydrated and pulverized bony fish skin, which is treated with chloroform and methanol (2:1 *v/v*) to remove lipids for 24 h at room temperature (Mecham 2008). This is followed by demineralization with 0.6 M hydrochloric acid for 24 h at 4°C (Debelle and Tamburro, 1999). To dissolve unwanted collagen, an alkaline solution is applied, using sodium hydroxide between 0.1 and 1.0 molar for 1 to 2 days at 37-45°C. This procedure results in a matrix enriched in elastin (Partridge and Davis, 1955). The sample is then centrifuged, obtaining the insoluble elastin in the process, washed with distilled water, and freeze-dried (Carvalho *et al*., 2024). Elastin has been incorporated into gels, dressings, and tissue

scaffolds, allowing for more adequate vascular and skin regeneration. In cosmetics, it has greater commercial use in the formulation of anti-ageing products (Daamen *et al*., 2007).

Marine biominerals

A. Hydroxyapatite

Calcium phosphate bioceramics have been gaining interest in the field of health sciences. This material has sparked the interest of researchers in the search for alternative sources to its commercial synthesis. Hydroxyapatite ($Ca_{10}(PO_4)_6(OH)_2$) has stood out for its chemical composition and structure similar to that of human bone. This compound has properties such as biocompatibility, osteoconductivity, and the ability to integrate into bone tissue without generating adverse immune responses. It is the material of choice for tissue engineering and bone regeneration applications (Dorozhkin, 2009). When hydroxyapatite crystallizes, it forms a hexagonal structure (space group P63/m) with a Ca:P molar ratio of 1:10, similar to the biological apatite found in human bone (Dorozhkin, 2009). This structure allows integration into human bone tissue, promoting cell proliferation and the formation of new tissue.

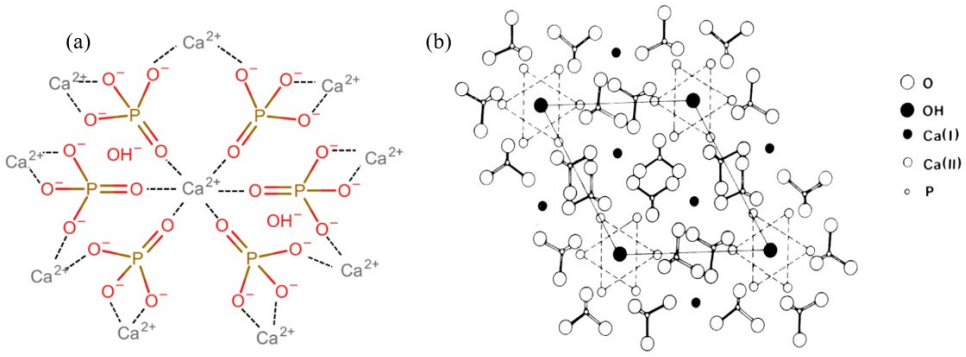


Figure 6. (a) Interpretation of the basal (001) plane from a top view with central calcium. (b) Projection of the basal (001) plane of the hydroxyapatite crystal lattice, taken from Rigano and Lionetti. O: oxygen, Ca: calcium, P: phosphorus, H: hydrogen.

Hydroxyapatite has been synthesized with high-purity chemicals; however, circular economy approaches have led to the use of marine waste for its production. In this case, fish skeletons, mollusk shells, and crustacean exoskeletons are an important source of calcium and phosphorus for obtaining biosynthetic hydroxyapatite.

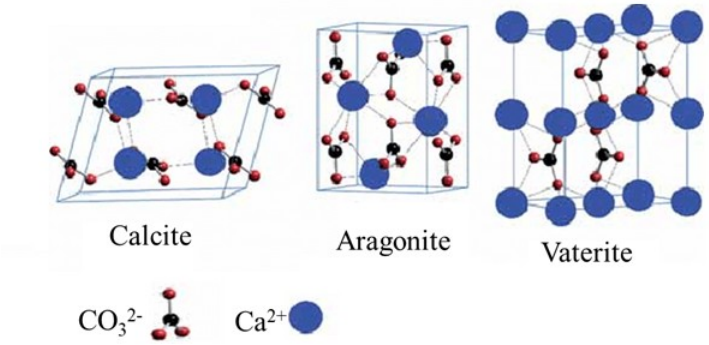
Fish bone waste (osteites) is calcined (600-900°C) to remove unwanted organic material and thus preserve the crystalline phase of hydroxyapatite (Karim *et al*., 2019). Shells, which are mainly

composed of calcium carbonate, require hydrothermal treatment or phosphate-assisted chemical conversion to generate hydroxyapatite (Fitriyana *et al*., 2024; Ivankovic *et al*., 2010). As for crustacean exoskeletons (processed in the same way as shells), in addition to containing up to 50% by weight of chitin, they also contain minerals that can be used for the synthesis of hydroxyapatite, which generates high-value-added products (Venkatesan and Kim, 2010). Additionally, it is possible to incorporate other elements such as magnesium, zinc, or strontium into the structure to modify its properties and confer antimicrobial activity (Lin *et al*., 2014).

The similarity of human bone to hydroxyapatite makes it an excellent substitute for coating implants, bone cements, porous scaffolds, and composite materials to facilitate osseointegration and tissue regeneration (Prabakaran and Rajeswari, 2006). Hydroxyapatite has also been used for controlled drug release, taking advantage of its high surface area and adsorption capacity. It has also been shown to reduce the side effects of antitumor drugs (Saber-Samandari *et al*., 2016). In another context, hydroxyapatite has applications in environmental remediation due to its ability to adsorb heavy metals such as lead, cadmium, and chromium in water through ion exchange, coprecipitation, and the formation of stable complexes (Balabadra *et al*., 2024).

B. Calcium carbonate

Tertiary inorganic salts are also part of biomaterials of industrial interest, notably calcium carbonate, which is easily obtained from some marine organisms such as oysters, mussels, clams, and crustacean shells such as crabs and lobsters, and is considered a low-cost natural source (Fernández-Penas *et al.,* 2023). Calcium carbonate is insoluble in water but sensitive to acids. It has three crystalline configurations: calcite, aragonite, and vaterite (Azarian and Sutapun, 2022). Aragonite is the most common crystalline configuration in marine organisms.



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Figure 7. Unit cells of the calcite, aragonite and vaterite configuration (Dizaj *et al*., 2015). O: oxygen, C: carbon, Ca: calcium.

The extraction of calcium carbonate begins with the collection and cleaning of waste from the fishing and aquaculture industries. Subsequently, a chemical treatment is carried out with 5-10% hydrogen peroxide or 3-6% sodium hypochlorite for 1-3 hours at room temperature to remove organic waste and nitrogen compounds (Barros *et al*., 2008).

The materials are then dried and pulverized using ball mills (Tsai et al., 2008), followed by calcination at 900°C (Ismail *et al*., 2022).

Calcium carbonate is purified by applying 1-2% diluted acetic acid to remove metallic impurities adhering to the material and then centrifuging to remove the aqueous phase. Finally, the carbonate is washed with distilled water until it reaches a neutral pH and dried (Permatasari *et al*., 2021).

Calcium carbonate is used as a biocompatible filler for the preparation of bone cements and as a precursor for the synthesis of hydroxyapatite. Its porous structure makes it a useful material as a three-dimensional scaffold for bone coating (Saharudin *et al*., 2018).

The food industry uses this biomaterial to produce supplements and formulas enriched with bioavailable calcium for nutritional applications (Xu *et al*., 2020). Other entities focused on the environment use calcium carbonate as a neutralizer of acidic effluents and/or as an adsorbent for heavy metals in wastewater treatment (Zhang *et al*., 2018). In the materials industry, calcium carbonate has been applied in the production of bioceramics and bioplastics (Owuamanam and Cree, 2020). The purpose of obtaining this biomaterial is to try to reduce the impact generated by waste from the aquaculture and fishing industries.

Technical and ethical limitations, future perspectives

Despite the vast marine biodiversity, the exploitation of marine fauna for the production of biomaterials poses critical ethical, ecological, and technical challenges.

Commercial pressure on specific species has raised serious ecological concerns. The demand for chondroitin sulfate and collagen has fueled the fishing of sharks and rays, leading the IUCN (International Union for Conservation of Nature) to classify several species as “vulnerable” or “near threatened” (Seixas *et al*., 2020). A prime example is the blue shark, which is caught incidentally in tuna fisheries, with landings reaching 440 metric tons annually in Portuguese

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waters alone (Seixas *et al*., 2020). This overexploitation for the fin and cartilage trade pushes these species to the brink of extinction and disrupts the trophic structure of marine ecosystems (Coppola *et al*., 2020), making it imperative that any extraction of biopolymers from these sources be strictly monitored and justified. Similarly, practices such as trawling for crustaceans degrade the marine benthos, while coral harvesting has a direct and irreversible impact on reefs (Clarke *et al*., 2012; Khrunyk *et al*., 2020).

From a technical perspective, processes such as the extraction of chitin and chitosan require the industry to use acid and alkali treatments that generate aggressive chemical effluents; furthermore, the quality of the final polymer is highly dependent on good manufacturing practices, as the nature of the process can degrade its structure (Batra *et al.,* 2023). Furthermore, extraction yields vary dramatically depending on the method and species; for example, pepsin-soluble collagen extracted from the blue shark (*Prionace glauca*) yields 3.5%, while acid-soluble collagen from the same species yields only 0.15% (Seixas *et al*., 2020). On the other hand, Hydroxyapatite is obtained mainly from the bone parts and scales of various fish species, achieving significant yields of up to 50-53% of their dry weight. In this process, the calcination temperature becomes the critical control variable for ensuring the material's properties (Boudreau *et al*., 2025; Harrel 2017). From an environmental perspective, the ecological costs of these processes are rarely factored into the final price of the product. Improper disposal of chemical effluents and fishery byproducts contributes to eutrophication, ocean acidification, and the creation of anoxic zones in benthic habitats that depend directly on the balance of crustaceans and mollusks (Batra *et al.*, 2023; Harrel 2017; Clarke *et al*., 2012).

This scenario complicates the application of traditional bioethical frameworks. When applying Beauchamp and Childress's principalist model to nonhuman organisms, the moral status of lower invertebrates remains a subject of debate, closely linked to their capacity to feel pain—unlike the existing consensus regarding teleost species and cephalopods (Seixas *et al*., 2020; Rahman, 2019; Rahman, 2021). Consequently, the act of sacrificing specimens for their biomedical structures comes into direct conflict with the principle of non-maleficence (Seixas *et al*., 2020; Rahman, 2019; Rahman, 2021).

For this reason, the circular economy is proposed as a strategy to minimize the environmental impact of fish waste and, at the same time, obtain economic benefits by converting it into resources for obtaining marine biomaterials. The ideal solution to meet the demand for these

biomaterials does not lie in irresponsibly shifting the pressure from terrestrial sources to marine organisms—or vice versa—but rather in implementing a truly sustainable sourcing approach. The key strategy is based on the valorization of byproducts from the fishing and aquaculture industries. More than 35% of the total weight of catches (skeletons, heads, and viscera) is currently discarded as waste, becoming a source of environmental pollution (Batra *et al*., 2023; Harrel 2017). Processing this residual biomass as a source of advanced biomaterials not only mitigates the accumulation of waste in landfills and prevents eutrophication but also eliminates the need for targeted fishing (Batra *et al*., 2023; Seixas *et al*., 2020; Harrel 2017; Clarke *et al*., 2012; Coppola *et al*., 2020; Rahman, 2019). This model is directly aligned with the principles of the circular economy and the UN Sustainable Development Goals, specifically SDG 12 (Responsible Consumption and Production) and SDG 14 (Life Below Water) (Clarke *et al*., 2012).

At the same time, controlled cultivation on marine farms is emerging as a viable biotechnological alternative to the direct extraction of wild marine life. Controlled production of marine sponges (such as *Chondrosia reniformis* and *Aplysina aerophoba*) and certain species of jellyfish has proven to be an efficient method for the sustainable harvesting of collagen and chitin without impacting wild populations (Clarke *et al*., 2012; Rahman, 2019; Rahman, 2021). Finally, Table 2 outlines the structural classification, cellular origin, and hydrolytic processing of the primary marine-derived biomaterials evaluated in this study.

Table 2. Structural classification, cellular origin, and hydrolytic processing of key marine-derived biomaterials.

Bioamaterial	Link type (orientation)	Monomers/Structural units	Cellular Location	Applied hydrolysis	References
Chitin	β-(1→4)	N-acetylglucosamine	extracellular (exoskeleton)	Acidic or alkaline	Jayakumar *et al*., 2010
Chitosan	β-(1→4)	N-acetylglucosamine and D-glucosamine (predominant)	obtained by deacetylation of chitin from the exoskeleton	Chemical (concentrated alkaline) or enzymatic (chitinases/ chitosanases)	Centeno-Bordones *et al*., 2024
Chondroitin sulfate	β-(1→4) and β-(1→3) alternating	D-Glucuronic acid and sulfated N-acetyl-D-galactosamine	Extracellular matrix	Enzymatic (chondroitinases) or mild chemistry	Prydz, 2015; Talmoudi *et al*., 2020
Collagen	Peptide	Glycine, proline, hydroxyproline	Extracellular matrix	Acidic, enzymatic (pepsin)	Ricard-Blum, 2010

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Gelatin	Peptide	Glycine, proline, hydroxyproline (denatured alpha chains)	obtained by thermal/chemical denaturation of collagen	Partial: Acidic (Type A) or alkaline (Type B)	Karim and Bhat 2009; Schrieber and Gareis 2007.
Elastin	Peptide and interchain (desmosine and isodesmosine)	Glycine, alanine, valine, and proline (precursor: tropoelastin)	Extracellular matrix	Partial: Specific enzymatic (elastases) or mild chemical treatment to preserve hydrophobic domains.	Almine *et al*., 2010; Ehrlich, 2014
Hydroxyapatite	Ionic / Covalent (crystal lattice)	Calcium, phosphate, and hydroxide ions	Extracellular matrix	Not applicable (subjected to thermal calcination or acid dissolution for extraction)	Dorozhkin, 2009; Fitriyana *et al*., 2024; Ivankovic *et al*., 2010
Calcium carbonate	Ionic (polymorphic crystal lattice: calcite, aragonite, or vaterite)	Calcium and Carbonate ions	Mineralized extracellular matrix	Not applicable (subjected to alkaline deproteinization/thermal washing or controlled leaching)	Azarian and Sutapun, 2022; Tsai *et al*., 2008; Ismail *et al*., 2022

Conclusions

The growing exploration of marine resources has revealed enormous potential in the development of biomaterials with biotechnological applications. Among these, compounds such as chitin, chitosan, hydroxyapatite, calcium carbonate, collagen, gelatin, and elastin stand out, all extracted from marine organisms such as crustaceans, fish, and mollusks. These biomaterials not only represent a sustainable alternative to those of terrestrial origin, but also offer properties that make them compatible with human biological systems. Their natural origin, abundance, and ability to be processed using clean and efficient techniques make them fundamental building blocks of marine biotechnology. Materials such as chitin and chitosan have antimicrobial, healing, and bioadhesive properties, making them ideal for applications in regenerative medicine, controlled drug delivery, and wound treatment. Their versatility also extends to chemical applications in water purification and the manufacture of biodegradable films, demonstrating their value in environmental biotechnology as well.

Marine collagen, along with its derivative gelatin, has gained prominence in the cosmetic, pharmaceutical, and food industries thanks to its ability to improve skin elasticity, promote

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healing, and act as a vehicle for bioactive compounds. In addition, its high biodegradability makes it a safe and environmentally friendly option. Elastin, although less abundant, provides essential mechanical properties in the formulation of antiaging products and in the creation of artificial tissues with characteristics similar to natural ones, revolutionizing the cosmetic and pharmaceutical industries. On the other hand, hydroxyapatite and calcium carbonate, compounds extracted from shells and crustaceans, bones, and fish scales, have revolutionized the field of bone tissue engineering. Their structural similarity to human bone tissue allows for efficient integration into implants, prostheses, and dental fillings, promoting regeneration and repair of damaged bone structures through the application of biocements.

From a biotechnological perspective, marine biomaterials enable the design of innovative solutions that respond to medical, pharmaceutical, cosmetic, environmental, and industrial challenges. Their study and application promote the circular economy by adding value to fishing by-products, thereby reducing environmental impact. In addition, they promote the development of clean, sustainable, and accessible technologies, especially in coastal regions where marine biodiversity is abundant. Research in the field of biomaterials generates new opportunities for the development of personalized medicine, nanobiotechnology, and tissue biofabrication, consolidating the importance of the oceans as a source of life and scientific innovation.

The future of marine biomaterials requires the establishment of rigorous international traceability and certification systems that decouple production from the harvesting of threatened species. A post-anthropocentric ethical framework must be adopted that prioritizes animal welfare and ecosystem integrity. Technical and supply constraints must be balanced within the framework of biodiversity sustainability, prioritizing the optimization of green chemical processes, waste mitigation, and the valorization of industrial byproducts as the only safe way to maximize economic value without compromising the ocean’s natural capital.

Acknowledgments. The authors would like to express their gratitude to Biologist Yanetza Linares for her valuable support and technical assistance throughout the development of this research.

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