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Review

Marine-Originated Materials and Their Potential Use in Biomedicine

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Abstract: Aquatic habitats cover almost 70% of the Earth, containing several species contributing to marine biodiversity. Marine and aquatic organisms are rich in chemical compounds that can be widely used in biomedicine (dentistry, pharmacy, cosmetology, etc.) as alternative raw biomaterials or in food supplements. Their structural characteristics make them promising candidates for tissue engineering approaches in regenerative medicine. Thus, seaweeds, marine sponges, arthropods, cnidaria, mollusks, and the biomaterials provided by them, such as alginate, vitamins, laminarin, collagen, chitin, chitosan, gelatin, hydroxyapatite, biosilica, etc., are going to be discussed focusing on the biomedical applications of these marine-originated biomaterials. The ultimate goal is to highlight the sustainability of the use of these biomaterials instead of conventional ones, mainly due to the antimicrobial, anti-inflammatory, anti-aging and anticancer effect.

Keywords: marine biomaterials; alginate; chitin; chitosan; hydroxyapatite; biosilica

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1. Introduction

Almost 70% of the Earth is covered by aquatic habitats, hosting a great biodiversity of flora and fauna [1]. Several of these marine and aquatic organisms play a crucial role in the ecosystem, provide raw materials and filters, and are capable of being consumed as seafood [2]. Nematodes, sponges, algae, bryozoans, fishes, cuttlefishes, and many others are among the aquatic organisms (invertebrates and vertebrates) that either produce toxins and chemical compounds, mainly for defense reasons, which can be used in pharmacy, or provide themselves with alternative raw biomaterials [3]. Chitin and chitosan, for instance, are biopolymers with antimicrobial potential [4], and hydrophobic luffa sponges have been proven efficient for oil removal from water [5]. Bryostatin is also a characteristic example of a very promising marine-originated pharmaceutical against melanoma, cell sarcoma, and other cancer types [6].

Seaweeds are categorized as brown algae (phylum *Ochrophyta*), red algae (phylum *Rhodophyta*), and green algae (phylum *Chlorophyta*), and each of these groups has different bioactivity [7]. The use of seaweeds in biomedicine has been well known since time immemorial, particularly in Asia [7]. Recently the antimicrobial, antithrombotic, anti-inflammatory, and anticancer effects of seaweed, and the use of them as a super food, make them an interesting candidate in sustainable pharmacy [8]. Seaweed can act also as a marker of specific pollutants, such as organochlorine pesticides and polycyclic aromatic hydrocarbons. They can rapidly detect any alteration in water chemistry, playing a crucial role in environmental protection [9]. Furthermore, seaweed can also be used as raw materials to produce bioplastics and cosmetic products. And it is worth mentioning that seaweeds can replace conventional fossil fuel resources, providing an eco-friendly and cost-effective energy alternative that is now more than urgent [10].

Marine sponges constitute the phylum *Porifera* categorized as *Metazoa* and are considered among the oldest multicellular animals worldwide [11]. They are sessile animals that are a source of a variety of biocompounds, such as spongin, chitin/chitosan, biosilica, and polyphosphate [12]. The structural features of marine sponges are also desirable for numerous environmental and biomedical applications. Thus, among other marine species, marine sponges might be exploited further in biomedicine and particularly in tissue engineering.

The phylum *Arthropoda*, or arthropods, contains marine species such as lobsters, crabs, shrimps, isopods, copepods and amphipods, crayfish, and other non-marine animals, like insects [13]. Crustacea is perhaps the most famous group of these species. Crustaceans, e.g., lobsters, crabs, shrimps, etc., are equipped with an external skeleton, rich in calcium carbonate to protect them [14]. Arthropods are a great source of chitin [15].

The phylum *Mollusca* contains cuttlefish, octopuses, squids, and nautiluses as well as oysters, clams, mussels, scallops, etc. [16]. These species, and particularly a certain part of them, like seashells and part of their skeleton (bone), contain aragonite, which can be easily hydrothermally transformed into hydroxyapatite [17]. Hydroxyapatite is a surface-reactive bioceramic. Due to its physicochemical properties, it can be used in hard tissue regenerative medicine [18,19]. Apart from biomedical applications, hydroxyapatite is can be used for the treatment of air, water, and soil pollution and for catalysis; thus, it can be used in the field of environmental management [20].

Finally, cnidaria and particularly jellyfishes and coral are also a great source of marine gelatin with various applications, in food, biomedicine, and hydroxyapatite.

In this review, we focus on the biomedical applications of marine-originated biomaterials, including food, pharmaceuticals, cosmetics, and tissue engineering, focusing on recent research advances. Since it is now well established that this topic seems to have a great impact in the field of biomaterials, any attempt that tries to shed light on the sustainability of the use of these biomaterials instead of conventional methods remains innovative. In our case, we aim to help experts of this field to find helpful data in a condensed manuscript.

2. Seaweed-Originated Components

Seaweeds are marine organisms that contribute to the vast biodiversity of the sea. Seaweeds are multicellular organisms (macroalgae) that differ from Earth plants due to the lack of roots, leaves, and stems [21]. Brown, red, and green algae are the main categories of seaweed, as has been mentioned [7]. Among various other renewable resources living in the marine environment, seaweeds can be used in environmental, paper and textile, food, cosmetics, and pharmaceutical applications [22–24]. Seaweeds are a major source of raw material for agar production due to the fact that they are rich in hydrophilic colloids (phycocolloids) [25]. Thus, mainly in Asia, seaweeds are consumed as gelling agents in the dietary and food industries [26]. Other seaweeds, such as *Sargassum wightii* (brown algae), are commonly used as food ingredients in soy sauce, in soups, and in other traditional Asian dishes due to their high food value.

Biomedical and Food Applications of Seaweed-Originated Components

Seaweeds have been thoroughly studied for their nutritional composition. Based on the rich bioactive compounds that are found in seaweeds, the wide use of them has been linked to a healthy and beneficial diet. Several analyses have shown that the levels of proteins, proline, lipids, polyphenols, chlorophyll contents, dietary fibers, and carbohydrates that are included in seaweeds are high [27]. Apart from proline, essential amino acids, such as methionine, lysine, valine, and phenyl alanine, are found in significant levels in seaweed's composition [28]. Furthermore, linolenic acid and α-linolenic acid, which are fatty acids with high nutritional value, and vitamins (mainly vitamin C) are among the main ingredients of seaweeds [29]. Thus, it is reasonable that seaweeds might be used as nutritional supplements. Many studies have thoroughly analyzed the composition of seaweeds, indicating that they are rich in essential minerals, such as iron, magnesium, calcium, potassium, zinc, selenium, copper, iodine, phosphorus, and fluoride [30]. Other studies have focused on the vitamins that are found in seaweeds, such as A, B1, B2, B9, B12, C, D, E, K, riboflavin, folic acid, and pantothenic acid. In particular, *Porphyra umbilicalis*, *Himanthalia elongata*, and *Crassiphycus changii* are among the species that are rich in vitamin C [8]. Syad et al., analyzing the nutritional composition of *G. acerosa* and *S. wightii*, proposed their use as potential food supplements [24]. Thus, the common point of these studies is that they propose seaweeds as low-caloric, nutritive foods [23].

Marine pharmaceuticals is a quite modern branch of pharmacology. The possible use of seaweed compounds for the development of natural drugs is among the scopes of this scientific field. Seaweeds have been used in biomedicine, mainly in Asian countries, since ancient times [7]. According to Arokiarajan et al., marine organisms, like algae, are a source of various bioactive compounds, such as sulfated polysaccharides, and although they are a defensive barrier against any infective organism, protecting algae, they might also be used in biomedicine, due to their anti-inflammatory, antitumor, antiviral, and antimicrobial potentials, which are mainly used in tissue engineering or in drug delivery system development [31]. Furthermore, various studies have indicated that seaweeds provide antioxidant and enzyme inhibitory effects [32]. Moreover, alkaloids, terpenoids, and steroids have been detected in brown algae (genus *Cystoseira*) in the Mediterranean Sea, and Amico et al. have focused on their pharmaceutical potential [33].

Brown seaweeds contain fucoidan rich in sulphate ester groups; L-fucose; monosaccharides, such as glucose and galactose; and uronic acids [34]. Pozharitskaya et al. have studied the pharmacokinetics of fucoidan of Fucus vesiculosus in their study involving post-administration to rats [35]. Generally, marine polysaccharides, e.g., fucoidan, have proven to be effective against herpes virus strains such as enterovirus (ECHO-1), human immunodeficiency virus (HIV-1), Herpes Simplex Virus type 1 (HSV-1), and Herpes Simplex Virus type 2 (HSV-2), according to Krylova et al. [36]. Kappaphycus, Chondrus, and Eucheuma red seaweed species contain carrageenan with antivirus potential against HSV-1 and HSV-2 in vitro [37]. Elatol from red algae has shown antibacterial properties against *Staphylococcus epidermidis*, *Salmonella* sp., and *Klebsiella pneumoniae* [38].

Also, laminarin and alginate are found in brown seaweeds. Laminarin is a linear polysaccharide that is mainly used in biomedicine. It has immunostimulatory activity, activating macrophages possessing antitumor and auto-healing properties [39]. It is worth mentioning that, upon irradiation with gamma rays, laminarin's antioxidant behavior is enhanced [40]. Alginate is a biopolymer, with very good stabilizing properties. It is used in food products and in medicine [41]. Particularly, it is widely used in dentistry for mold making, in the whitening process, and for artificial dental implants [42] and is also used as a bio-ink in 3-D bioprinting [43].

Terpenoids and terpens are found in algae. Numerous studies have indicated that they might be used as anticancer agents and have focused on the possible therapeutic effect of them on lung, breast, prostate, colon, and pancreatic cancer cells [44]. Other studies have shown that seaweed phytosterols, e.g., fucosterol, can reduce cholesterol levels presenting several beneficial properties, such as anti-diabetic, anti-obesity, anti-aging, and anticancer effects [45].

Cosmeceuticals is considered a cosmetology field focusing on the use of bioactive ingredients [21]. Recently, macroalgae extracts have gained interest due to their benefits for the treatment of skin disorders and their anti-inflammatory and anti-aging properties [46]. Table 1 summarizes the biomedical and food applications of seaweed-originated components.

Potential Risk of Seaweed-Originated Components

In addition to the benefits of the bioactive compounds of the seaweeds, some studies have reported that they can accumulate cadmium (Cd), copper (Cu), mercury (Hg), lead (Pb), arsenic (As), and other toxic metals [47]. These findings mean that possible health problems could arise upon the consumption of some seaweed species. The European Union has not yet published related legislation about the upper limits of the consumption of seaweeds. Only France has issued some recommendations in the frame of food safety [48].

Table 1. Biomedical and food applications of seaweed-originated components.

Seaweed-Originated Component	Source	Application	Ref.
vitamins (vitamins A, B1, B2, B9, B12, C, D, E, and K), riboflavin, folic acid, and pantothenic acid	brown seaweeds (*Cystoseira crinita*, *Cystoseira sedoides* and *Cytosmear compressa*)	food (healthy diet, nutritional supplements)	[8]
proteins, vitamins, minerals, dietary fiber, polyphenols, polysaccharides, sterols, essential fatty acids such as eicosapentaenoic (EPA), and docosahexaenoic (DHA) fatty acids	seaweeds (*Porphyra/Pyropia* spp. (*Nori*), *Laminaria/Saccharina* spp. (*Kombu*), and *Undaria* spp. (*Wakame*))	food (healthy diet, low-caloric, nutritive food)	[23]
dietary fibers and polyphenols, carbohydrates, proteins, lipids, proline and chlorophyll contents, potassium, sodium, and fatty acids	red and brown seaweeds (*G. acerosa* and *S. wightii*)	food (healthy diet, food supplements)	[24]
proteins, proline, lipids, polyphenols, chlorophyll contents, dietary fibers, and carbohydrates	green seaweeds (*Ulva lactuca*, *U. prolifera* and *U. linza*, *Enteromorpha intestinalis*, *Caulerpa* spp., *Cladophora prolifera*, *C. vermilara*, and *C. tomentosum*) and	food (healthy diet)	[27]
essential amino acids, such as methionine, lysine, valine, and phenyl alanine	macroalgae (*Porphyra dioica*, *Porphyra umbilicalis*, *Gracilaria vermiculophylla*, and *Ulva rigida*)	food (healthy diet)	[28]
linolenic acid and α-linolenic acid (fatty acids) and vitamins (vitamin C)	green seaweeds (*Caulerpa lentillifera*)	food (healthy diet, nutritional supplements)	[29]
essential minerals (e.g., iron, magnesium, calcium, potassium, zinc, selenium, copper, iodine, phosphorus, and fluoride)	macroalgae (*Ulva rigida*, *Saccharina latissima*, *Laminaria digitata*, and *Laminaria hyperborean*)	food (healthy diet, nutritional supplements)	[30]
sulfated polysaccharides	marine algae (*Phaeophyta*, *Rhodophyta* and *Chlorophyta*)	biomedicine (drug delivery systems, tissue engineering): defensive barrier against any infective organism) with anti-inflammatory, antitumor, antiviral, and antimicrobial properties	[31]
fiber, mineral content, fats and lipids, and vitamin contents	seaweeds (*Ascophyllum nodosum*, *Laminaria digitata*, *Himanthalia elongate*, *Undaria pinnatifida* *Porphyra umbilicalis*, *Ulva* sp., *Palmaria palmata*, and *Enteromorpha* sp.)	biomedicine (drug delivery systems): antioxidant and enzyme inhibitory effects	[32]

Table 1. *Cont.*

Seaweed-Originated Component	Source	Application	Ref.
alkaloids, terpenoids, and steroids	brown seaweeds (*Genus Cystoseira*)	biomedicine (pharmaceutical potential): alkaloids, terpenoids, and steroids in brown algae (genus *Cystoseira*) in Mediterranean Sea	[33]
fucoidan, rich in sulphate ester groups; L-fucose; monosaccharides (e.g., glucose, and galactose); and uronic acids.	brown seaweeds (*Fucus vesiculosus*)	biomedicine (pharmaceutical potential)	[34]
fucoidan	brown seaweeds (*Fucus vesiculosus*)	biomedicine (pharmaceutical potential): pharmacokinetics of fucoidan following administration to rats;	[35]
fucoidan	brown algae (*Fucus evanescens*)	biomedicine (antiviral properties): antiviral potential of fucoidan against herpes virus strains such as enterovirus (ECHO-1), human immunodeficiency virus (HIV-1), Herpes Simplex Virus type 1 (HSV-1), and Herpes Simplex Virus type 2 (HSV-2)	[36]
lambda-carrageenan	red seaweeds (*Kappaphycus*, *Chondrus*, and *Eucheuma* sp.)	biomedicine (antiviral properties): antiviral potential against HSV-1 and HSV-2 in vitro	[37]
elatol	malaysian red algae (*Laurencia majuscula* (*Rhodomelaceae*, and *Ceramiales*))	biomedicine (antimicrobial potential): antimicrobial properties against *Staphylococcus epidermidis*, *Salmonella* sp., and *Klebsiella pneumoniae*	[38]
laminarin	brown seaweeds (*Aphanizomenon flos-aquae*)	biomedicine (pharmaceutical potential): immunostimulatory activity, activation of macrophages with antitumor and auto-healing properties	[39]
laminarin	brown seaweeds (*Eisenia bicyclis*)	biomedicine (pharmaceutical potential): enhanced antioxidant behavior of laminarin upon irradiation with gamma rays	[40]
alginate	brown algae (*Laminaria hyperborea*, *Laminaria digitata*, *Laminaria japonica*, *Ascophyllum nodosum*, and *Macrocystis pyrifera*)	food and biomedicine	[41]
alginate	Phaeophyceae family	biomedicine (dentistry): mold making in whitening process or for artificial dental implants	[42]
alginate	brown algae	biomedicine (tissue engineering): 3-D bioprinting; alginate as a bio-ink	[43]
terpenoids and terpens	algae	biomedicine (anticancer potential): anticancer properties (therapeutic effect on lung, breast, prostate, colon, and pancreatic cancer cells)	[44]
phytosterols (e.g., fucosterol)	Macroalgae (brown, red, and green algae)	biomedicine (pharmaceutical potential): seaweed phytosterols reduce cholesterol levels with beneficial properties (anti-diabetic, anti-obesity, anti-aging, and anticancer properties)	[45]
R-Phycoerythrin (R-PE)	red algae (*Rodophyta*) (*Corallina elongata Ellis* and *Solander*)	biomedicine (cosmetology): skin disorders with anti-inflammatory and anti-aging properties	[46]

3. Marine Sponge-Originated Components

Marine sponges, a Porifera species, can offer numerous biomaterials that are part of their chemical composition [49]. Their structure allows them to be used in environmental, anti-pollutant agents. Also, commercial sponges derived from natural sponges (commercial sponges can be synthetic or natural if they can be collected from dead natural sponges, dried, and used for commercial purposes) can be utilized particularly against water pollutants and oil spills [50]. Natural sponges have significant advantages over synthetic ones. They are long-lasting, more absorbent, and odor repellent with a soft texture [12]. Actually, sponges play an important role in ecology since they act as indicators of ocean pollution. Also, the biomedical applications of marine sponges are mainly related to chitin, biosilica, and polyphosphate, which are found to be abundant in them, and are associated with their ability to biomineralize, forming bioglass [51].

Biomedical Applications of Marine Sponge-Originated Components

Marine sponges are rich in secondary metabolites of pharmaceutical significance. Most of them are microbial origins, which symbiotically exist due to sponges [52]. Terpenes, alkaloids, and peptides are among the main metabolites produced by marine sponges. de Silva et al. have isolated manoalide from sponge *L. variabilis* in Palau [53]. This compound exhibited antibacterial activity against *Streptomyces pyogenes* and *S. aureus*. Manoalide, according to Ortiz et al., could inhibit the activity of the phospholipase A2 (PLA2) enzyme that provides a substrate of pro-inflammatory mediators [54]. Isomalabaricanes are triterpenes found in marine sponges. They can be classified into stelletins, stelliferins, and globostellatic acids [12]. Su et al. have indicated that stelletins from *J. stellifera* and *Stelleta tenuis* are cytotoxic to murine leukemia P388 cells [55]. Manzamine A, an alkaloid isolated from *Haliclona* sp., has shown cytotoxic, anti-malarial, and antibacterial activity [56]. Discodermin A, a peptide detected in Discodermia kiiensis (and in discodermins B, C, and D) has exhibited antibacterial potential, inhibiting PLA2 [57].

Clathric acid from Clathria compressa [58] and motualevic acid from *Siliquariaspongia* sp. [59] could inhibit the growth of methicillin-resistant *S. aureus*. Metachromin A from *Dactylospongia metachromia* inhibited Hepatitis B viral production [60]. Xestodecalactone B isolated from Xestospongia exigua could inhibit the growth of *C. albicans* [61].

Zhou et al. isolated from *Aspergillus* sp. Misszrtine A, an alkaloid with anticancer effects on HL-60 and LNCap cells [62]. Also, gracilosulfates A, B, C, D, E, F, and G, which are steroids found in *Haliclona gracilis*, has shown anti-tumor activity in human prostate cancer [63]. Monacolin X, a polyketide isolated from *Monascus* sp., showed a significant anti-proliferative and anti-migratory effect on human breast cancer cells [64].

Silicon dioxide (SiO_2) or silica can be synthesized by marine sponges to form their skeletal elements. Thus, this type of silica is widely known as biosilica (biogenously formed polymeric silica) [65]. Biosilica has numerous areas of application, such as in sensoring, coating, and the development of hybrid materials and drug delivery systems [66]. Also, it can be used with positive effects on cartilage and bone healing; thus, it can be used in tissue engineering to form scaffolds [67].

Polyphosphates are inorganic compounds that are produced from various animals and are also present in the skeletons of marine sponges. According to various studies, this substance has an osteogenic role. Lowe et al. have shown that polyphosphates enhanced the mineralization of osteoblast-like SaOS-2 cells [68]. Skaggs et al. indicated that polyphosphates upregulated collagen type I and II levels in osteogenic and chondrogenic cells [69]. Thus, polyphosphates should be used in regenerative medicine, and mainly in bone repair and bone therapies, due to biomimetic behavior.

Collagen-like protein (spongin) can be extracted from marine sponges, such as *Axinella cannabina* and *Suberites carnosus* [70]. Spongin has ideal properties, regarding porosity, thermostability, and mechanical strength, and, hence, it can be used in tissue engineering [71]. Spongin-based scaffolds have been isolated from *Demosponge Hippospongia* communis and used as a template for the hydrothermal deposition of crystalline titanium dioxide, with potential use in biomedicine [72].

Chitin is a very famous biopolymer present in many organisms, including marine sponges and arthropods [73]. Thermostability, biocompatibility, and biodegradation, in parallel with good mechanical properties, are the major advantages of chitin to be used in applications, such as drug delivery system development and tissue engineering (wound healing, scaffolds, etc.) [74]. Chitin can also be used in biosensing and as a water filter since it can be stable even in high-temperature and high-pressure conditions [75]. Table 2 presents some of the most significant biomedical applications of marine-sponge-originated components.

Table 2. Biomedical applications of marine-sponge-originated components.

Marine-Sponge-Originated Component	Source	Application	Ref.
terpenes, alkaloids, and peptides	marine sponges	biomedicine	[52]
manoalide	sponge *L. variabilis*	biomedicine (antimicrobial properties): antibacterial activity against *Streptomyces pyogenes* and *S. aureus*	[53]
stelletins	*J. stellifera* and *Stelleta tenuis*	biomedicine (anticancer potential): stelletins are cytotoxic to murine leukemia P388 cells	[55]
manzamine A	*Haliclona* sp.	biomedicine (pharmaceutical potential): cytotoxic, anti-malarial, and antibacterial activity of the alkaloid manzamine A	[56]
discodermin A	*Discodermia kiiensis*	biomedicine (antibacterial properties): antibacterial potential of the peptide discodermin A	[57]
clathric acid	*Clathria compressa*	biomedicine (antimicrobial properties): inhibition of the growth of methicillin-resistant *S. aureus* in the presence of clathric acid	[58]
motualevic acid	*Siliquariaspongia* sp.	biomedicine (antimicrobial properties): inhibition of the growth of methicillin-resistant *S. aureus* in the presence of motualevic acid	[59]
metachromin A	*Dactylospongia metachromia*	biomedicine (antiviral properties): antiviral potential of metachromin A against Hepatitis B	[60]
xestodecalactone B	*Xestospongia exigua*	biomedicine (antifungal properties): antifungal potential of xestodecalactone B against *C. albicans*	[61]
misszrtine A	*Aspergillus* sp.	biomedicine (anticancer potential): anticancer effect of the alkaloid misszrtine A on HL-60 and LNCap cells	[62]
gracilosulfates A, B, C, D, E, F, and G	*Haliclona gracilis*	biomedicine (anticancer potential): anticancer effect of the steroids gracilosulfates A, B, C, D, E, F, and G in human prostate cancer	[63]
monacolin X	*Monascus* sp.	biomedicine (anticancer potential): anti-proliferative and anti-migratory effect of the polyketide monacolin X on human breast cancer cells	[64]
Silicon dioxide (SiO_2) or silica (biosilica)	marine sponges	biomedicine (sensoring, coating, material science, tissue engineering, and drug delivery systems): sensoring, coating, and development of hybrid materials and drug delivery systems	[65,66]
biosilica	marine sponges	biomedicine (tissue engineering (scaffolds)): cartilage and bone healing	[67]
polyphosphates	marine sponges	biomedicine (regenerative medicine): enhancement of the mineralization of osteoblast-like SaOS-2 cells	[68]

Table 2. *Cont.*

Marine-Sponge-Originated Component	Source	Application	Ref.
polyphosphates	marine sponges	biomedicine (regenerative medicine (bone repair, biomimetic performance): upregulation of collagen type I and II levels in osteogenic and chondrogenic cells in the presence of polyphosphates	[69]
spongin	marine sponges	biomedicine (tissue engineering (scaffolds)): good porosity, thermostability, and mechanical strength of spongin	[71]
spongin	*Demosponge Hippospongia* communis	biomedicine (tissue engineering (scaffolds)): spongin as a template for hydrothermal deposition of crystalline titanium dioxide	[72]
chitin	marine sponges	biomedicine (tissue engineering, drug delivery systems): high thermostability, biocompatibility, biodegradation, and good mechanical properties of chitin	[74]
chitin	marine sponges	biomedicine (biosensoring, water filter): high stability of chitin even in high-temperature and high-pressure conditions	[75]

To sum up, marine-based materials have shown promising properties, and the main applications of them are schematically presented in Figure 1.

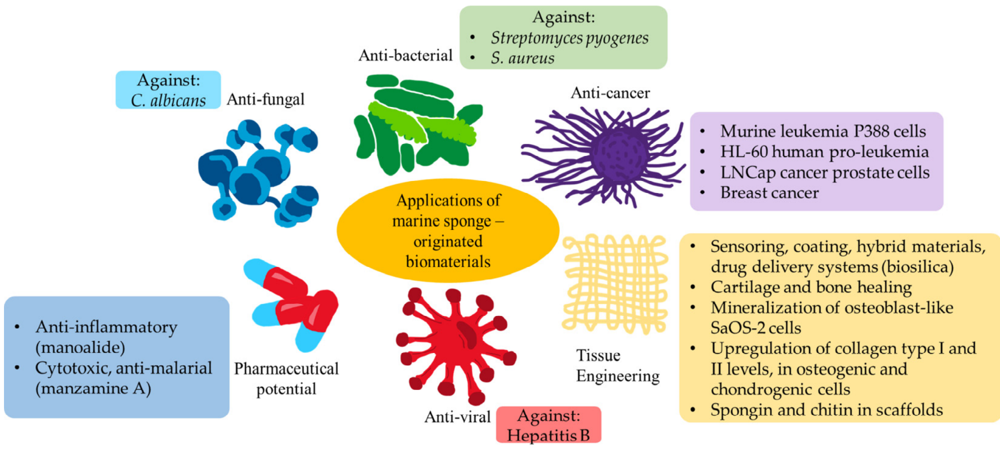

Figure 1. The applications of marine-sponge-originated biomaterials.

4. Arthropod-Originated Components and Their Biomedical Applications

Arthropods and particularly crustacea such as crabs, shrimps, and lobsters are a great source of calcium carbonate, silk, chitin, and chitosan [14,15,76]. Most of them have an outer skeleton, consisting of chitin–protein fibers and precipitated calcium carbonate within the chitin matrix for protection [77].

Applications of chitin derived from marine organisms, such as sponges, have been already mentioned. Chitosan is a polysaccharide that is obtained by the deacetylation of chitin and is available in crustaceans shells. In biomedicine, chitosan is used due to its high solubility and its active sites [73]. The wide use of chitosan in drug delivery systems and in tissue engineering are quite well known, but it is also worth mentioning the applications of chitosan in dentistry (wound healing, tissue engineering, and antimicrobial activity) [78].

Calcium carbonate is naturally available in the shells of crustaceans such as crabs and shrimps. The source of calcium is the water itself. In ocean water, the concentration of calcium is high. Thus, crustacea store calcium using a biomineralization process. Calcium carbonate in their exoskeletons, acting as a biomineral, can be used in regenerative medicine to form scaffolds or 3D templates for bone repair [79].

Silk is another promising biomaterial that is found in crustacea [80,81]. Silk is a protein-based biomaterial produced by arthropods, among other animals [81]. It has a great variety of applications, including in the textile industry and optoelectronics, due to its physicochemical and mechanical properties. The biocompatibility of silk allows its use in tissue engineering, regenerative medicine, and cosmetics. The sustainability and biodegradability of silk-based biomaterials make them desirable [76]. Silk can be used to enhance composite materials. Kim et al. created a PEG–silk hydrogel mimicking the structure of cartilage [82]. Silk fibers and hyaluronic acid were used by Yu et al. to develop a scaffold for biomedical use, supporting the cellular proliferation of bone marrow mesenchymal stem cells [83]. A vascular graft made of elastin–silk fibroins was implanted into the aorta of rats with stability and few side effects [84]. Silk can also be used in combination with hydroxyapatite for coating to improve its performance in bone tissue engineering [85]. These studies have focused on silk sericin and fibroin, particularly obtained from silk cocoons. However, the similarities between cocoon-derived silk and that obtained by crustacea allow us to think about several biomedical applications of marine-originated silk. Kakui et al. have shown that shrimp-like ocean crustaceans, known as tanaids, produce silk for shelter and safety, anchoring to rocks. Thus, this new type of silk could be used in environmentally friendly, water-resistant materials for fabrics; medical uniforms; and numerous other biomedical applications [86].

Table 3 presents the main biomedical applications of arthropod-originated components.

Table 3. Biomedical applications of arthropod-originated components.

Arthropod-Originated Component	Source	Application	Ref.
chitosan	crustaceans' shells	biomedicine (tissue engineering, drug delivery systems): high solubility and active sites	[73]
chitin	marine crab shells	biomedicine (tissue engineering, drug delivery systems, biosensoring, and water filter): several biomedical applications of chitin due to its good properties	[74,75]
chitosan	crabs	biomedicine (dentistry, wound healing, antimicrobial activity)	[78]
calcium carbonate	crabs and shrimps	biomedicine (regenerative medicine): scaffolds or 3D templates for bone repair	[79]
silk	arthropods	biomedicine (regenerative medicine, tissue engineering, cosmetics): biocompatibility	[76]
silk in combination with hydroxyapatite	Silk cocoons and mollusks	biomedicine (tissue engineering, bone repair): coating in bone tissue engineering	[85]
silk	shrimp-like ocean crustaceans	biomedicine and environment (tissue engineering, bone repair): environmentally friendly water-resistant materials for fabrics and medical uniforms	[86]

In summary, arthropod-derived biomaterials are mainly used in regenerative medicine, drug delivery systems, and dentistry, possessing also antimicrobial properties.

5. Mollusk-Originated Components and Their Biomedical Applications

Mollusks such as cuttlefishes, octopuses, squids, oysters, and mussels are great sources of aragonite and, consequently, of hydroxyapatite [17]. Hydroxyapatite is a widely used bioceramic due to its ideal properties. Actually, it is a calcium phosphate ($Ca_{10}(PO_4)_6(OH)_2$) (Figure 2) that is used in environmental and biomedical applications.

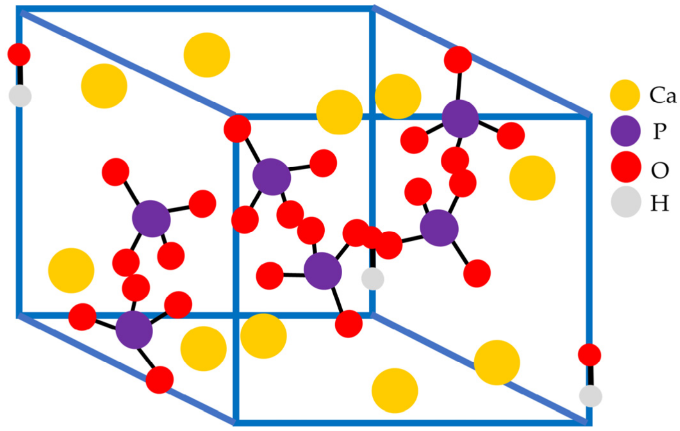

Figure 2. Schematical representation of hydroxyapatite.

Hydroxyapatite artificial implants are very popular in applications of hard tissue replacements. This material allows the acceleration of bone growth assisting the implant to be incorporated [87]. Corals and mollusks can provide hydroxyapatite, and its microstructure is similar to the inorganic mineralized structure of natural bones [88]. Thus, various studies have focused on the possible use of marine-derived hydroxyapatite obtained from cuttlefish bone from *Sepia officinalis* via hydrothermal transformation because it can help make procedures low-cost and eco-friendly. Also, the porosity and bioactivity of this material allows its use in scaffold development [17].

Hydroxyapatite also has a close analogy to the inorganic portion of human teeth. The enamel, which is the external layer of a human tooth, consists of ~97% inorganic compounds, and the dentine consists of ~70% inorganic material, with hydroxyapatite being the main part of this inorganic phase. Thus, it is used as a biomaterial in dentistry for implants [89]. Table 4 gathers some biomedical applications of marine-originated hydroxyapatite.

Table 4. Biomedical applications of mollusk-originated hydroxyapatite.

Mollusk-Originated Component	Source	Application	Ref.
hydroxyapatite	cuttlefish bone from *Sepia officinalis*	biomedicine and environment (tissue engineering, bone repair)	[17]
hydroxyapatite	mollusks	biomedicine and environment (tissue engineering, bone repair): artificial implants	[87]
hydroxyapatite	mollusks and corals	biomedicine and environment (tissue engineering, bone repair)	[88]
hydroxyapatite	Green mussel shells (*Perna canaliculus*) and *Evechinus chloroticus* shells	biomedicine and environment (dentistry)	[89]

6. Cnidaria-Originated Components and Their Biomedical Applications

Jellyfishes and corals are members of the phylum cnidaria. Corals are rich in hydroxyapatite, and the main applications of it have already been mentioned. Jellyfishes are a source of gelatin, which is also obtained from other species, such as mammalians [90].

Gelatin is commonly obtained by the hydrolysis of collagen. Type A gelatin can be produced from jellyfish and is widely used for food applications. Due to its emulsifying and foaming properties, it can also be used in pharmacy (tablets coating, carriers, etc.); cosmetics (emulsion stabilizers, etc.); and biomedicine, particularly in wound healing and tissue engineering [91].

More specifically, gelatin can be applied in numerous cosmetic products, including body lotions, face creams, hair sprays, sunscreens, shampoos, etc. [92]. Their antioxidant, antimicrobial, and anticancer potentials have also been studied. Hydrolyzed gelatin has shown an anticancer effect against MCF-7 breast cancer cells and U87 glioma cells [93]. Furthermore, antihypertensive peptides from gelatin have been shown by Lv et al. [94]. Thus, there is a great variety of applications of gelatin due to its structural and physicochemical properties. Table 5 gathers some of the most significant biomedical applications of cnidaria-originated components.

Table 5. Biomedical applications of cnidaria-originated components.

Cnidaria-Originated Component	Source	Application	Ref.
gelatin	jellyfish	biomedicine	[90]
type A gelatin	jellyfish	food	[91]
type A gelatin	jellyfish	biomedicine (pharmaceutical, cosmetics, tissue engineering): emulsifying and foaming properties in pharmacy (tablets coating, carriers, etc.), cosmetics (emulsion stabilizer, etc.), and biomedicine (wound healing and tissue engineering)	[91]
gelatin	fish and jellyfish	biomedicine (cosmetology): body lotions, face creams, hair sprays, sunscreens, and shampoos	[92]
hydrolyzed gelatin	jellyfish	biomedicine (anticancer potential): anticancer effect against MCF-7 breast cancer cells and U87 glioma cells	[93]
peptides of gelatin	fish and jellyfish	biomedicine (pharmaceutical potential): antihypertensive properties	[94]

7. Conclusions

Since the sources of raw materials are non-renewable, and the conventional chemical methods are not always eco-friendly, it is important to find alternative solutions to obtain biomaterials. Thus, aquatic habitats are a great solution due to the diversity, availability, and sustainability of marine organisms. Marine organisms are rich in a great variety of chemical compounds with potential biomedical applications. Their physicochemical and mechanical properties allow the wide use of these materials in tissue engineering, pharmacy, food industry, cosmetics, etc.

Biomaterials such as chitin, chitosan, alginate, gelatin, hydroxyapatite, biosilica, etc., can be isolated from marine organisms (e.g., seaweeds, marine sponges, arthropods, cnidaria, and mollusks), and their properties are comparable to those obtained from different sources. Thus, it is of crucial importance to gradually exploit the potential of marine organisms to develop advanced biomaterials.

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References

1. Dijkstra, K.D.; Monaghan, M.T.; Pauls, S.U. Freshwater biodiversity and aquatic insect diversification. *Annu. Rev. Entomol.* **2014**, *59*, 143–163. [CrossRef] [PubMed]
2. Boyd, C.E.; McNevin, A.A.; Davis, R.P. The contribution of fisheries and aquaculture to the global protein supply. *Food Secur.* **2022**, *14*, 805–827. [CrossRef] [PubMed]
3. Wijffels, R.H. Potential of sponges and microalgae for marine biotechnology. *Trends Biotechnol.* **2008**, *26*, 26–31. [CrossRef]
4. Casadidio, C.; Peregrina, D.V.; Gigliobianco, M.R.; Deng, S.; Censi, R.; Di Martino, P. Chitin and Chitosans: Characteristics, Eco-Friendly Processes, and Applications in Cosmetic Science. *Mar. Drugs* **2019**, *17*, 369. [CrossRef] [PubMed]
5. Alvarado-Gómez, E.; Tapia, J.I.; Encinas, A. A sustainable hydrophobic luffa sponge for efficient removal of oils from water. *Sustain. Mater. Technol.* **2021**, *28*, e00273. [CrossRef]
6. Khalifa, S.A.M.; Elias, N.; Farag, M.A.; Chen, L.; Saeed, A.; Hegazy, M.F.; Moustafa, M.S.; Abd El-Wahed, A.; Al-Mousawi, S.M.; Musharraf, S.G.; et al. Marine Natural Products: A Source of Novel Anticancer Drugs. *Mar. Drugs* **2019**, *17*, 491. [CrossRef]
7. Lomartire, S.; Gonçalves, A.M.M. An Overview of Potential Seaweed-Derived Bioactive Compounds for Pharmaceutical Applications. *Mar. Drugs* **2022**, *20*, 141. [CrossRef] [PubMed]
8. Mhadhebi, L.; Mhadhebi, A.; Robert, J.; Bouraoui, A. Antioxidant, Anti-inflammatory and Antiproliferative Effects of Aqueous Extracts of Three Mediterranean Brown Seaweeds of the Genus Cystoseira. *Iran. J. Pharm. Res.* **2014**, *13*, 207–220.
9. Zokm, G.M.E.; Ismail, M.M.; Okbah, M.A.E. Seaweed as bioindicators of organic micropollutants polycyclic aromatic hydrocarbons (PAHs) and organochlorine pesticides (OCPs). *Environ. Sci. Pollut. Res.* **2022**, *29*, 34738–34748. [CrossRef]
10. Farghali, M.; Mohamed, I.M.A.; Osman, A.I.; Rooney, D.W. Seaweed for climate mitigation, wastewater treatment, bioenergy, bioplastic, biochar, food, pharmaceuticals, and cosmetics: A review. *Environ. Chem. Lett.* **2023**, *21*, 97–152. [CrossRef]
11. Taylor, M.W.; Radax, R.; Steger, D.; Wagner, M. Sponge-associated microorganisms: Evolution, ecology, and biotechnological potential. *Microbiol. Mol. Biol. Rev.* **2007**, *71*, 295–347. [CrossRef] [PubMed]
12. Varijakzhan, D.; Loh, J.Y.; Yap, W.S.; Yusoff, K.; Seboussi, R.; Lim, S.E.; Lai, K.S.; Chong, C.M. Bioactive Compounds from Marine Sponges: Fundamentals and Applications. *Mar. Drugs* **2021**, *219*, 246. [CrossRef] [PubMed]
13. Brown, M.R.; Sieglaff, D.H.; Rees, H.H. Gonadal ecdysteroidogenesis in arthropoda: Occurrence and regulation. *Annu. Rev. Entomol.* **2009**, *54*, 105–125. [CrossRef]
14. Bentov, S.; Aflalo, E.D.; Tynyakov, J.; Glazer, L.; Sagi, A. Calcium phosphate mineralization is widely applied in crustacean mandibles. *Sci. Rep* **2016**, *6*, 22118. [CrossRef]
15. Zhang, H.; Wu, X.; Quan, L.; Ao, Q. Characteristics of Marine Biomaterials and Their Applications in Biomedicine. *Mar. Drugs* **2022**, *20*, 372. [CrossRef] [PubMed]
16. Pila, E.A.; Sullivan, J.T.; Wu, X.Z.; Fang, J.; Rudko, S.P.; Gordy, M.A.; Hanington, P.C. Haematopoiesis in molluscs: A review of haemocyte development and function in gastropods, cephalopods and bivalves. *Dev. Comp. Immunol.* **2016**, *58*, 119–128. [CrossRef]
17. Lagopati, N.; Agathopoulos, S. Hydroxyapatite Scaffolds Produced from Cuttlefish Bone via Hydrothermal Transformation for Application in Tissue Engineering and Drug Delivery Systems. In *Marine-Derived Biomaterials for Tissue Engineering Applications*; Choi, A., Ben-Nissan, B., Eds.; Springer Series in Biomaterials Science and Engineering; Springer: Singapore, 2019; Volume 14, pp. 179–205. [CrossRef]
18. Seyhan, S.A.; Alkaya, D.B.; Cesur, S.; Oktar, F.N.; Gunduz, O. Preparation and characterization of pure natural hydroxyapatite derived from seashells for controlled drug delivery. *J. Aust. Ceram. Soc.* **2022**, *58*, 1231–1240. [CrossRef]
19. Venkatesan, J.; Anil, S. Hydroxyapatite Derived from Marine Resources and their Potential Biomedical Applications. *Biotechnol. Bioproc. E* **2021**, *26*, 312–324. [CrossRef]
20. Ibrahim, M.; Labaki, M.; Giraudon, J.-M.; Lamonier, J.-F. Hydroxyapatite, a multifunctional material for air, water and soil pollution control: A review. *J. Hazard. Mater.* **2020**, *383*, 121139. [CrossRef] [PubMed]
21. Salehi, B.; Sharifi-Rad, J.; Seca, A.M.L.; Pinto, D.C.G.A.; Michalak, I.; Trincone, A.; Mishra, A.P.; Nigam, M.; Zam, W.; Martins, N. Current Trends on Seaweeds: Looking at Chemical Composition, Phytopharmacology, and Cosmetic Applications. *Molecules* **2019**, *24*, 4182. [CrossRef]
22. Kumar, M.; Gupta, V.; Kumari, P.; Reddy, C.R.K.; Jha, B. Assessment of nutrient composition and antioxidant potential of Caulerpaceae seaweeds. *J. Food Compost. Anal.* **2011**, *24*, 270–278. [CrossRef]
23. Peñalver, R.; Lorenzo, J.M.; Ros, G.; Amarowicz, R.; Pateiro, M.; Nieto, G. Seaweeds as a Functional Ingredient for a Healthy Diet. *Mar. Drugs* **2020**, *18*, 301. [CrossRef] [PubMed]

24. Syad, A.N.; Shunmugiah, K.P.; Kasi, P.D. Seaweeds as nutritional supplements: Analysis of nutritional profile, physicochemical properties and proximate composition of G. acerosa and S. wightii. *Biomed. Prev. Nutr.* **2013**, *3*, 139–144. [CrossRef]
25. Prasad, K.; Siddhanta, A.K.; Ganesan, M.; Ramavat, B.K.; Jha, B.; Ghosh, P.K. Agars of Gelidiella acerosa of west and southeast coasts of India. *Bioresour. Technol.* **2007**, *98*, 1907–1915. [CrossRef] [PubMed]
26. Ruperez, P.; Calixto, F.S. Dietary fibre and physicochemical properties of edible Spanish seaweeds. *Eur. Food Res. Technol.* **2001**, *212*, 349–354. [CrossRef]
27. Xu, J.; Liao, W.; Liu, Y.; Guo, Y.; Jiang, S.; Zhao, C. An overview on the nutritional and bioactive components of green seaweeds. *Food. Prod. Process Nutr.* **2023**, *5*, 18. [CrossRef]
28. Machado, M.; Machado, S.; Pimentel, F.B.; Freitas, V.; Alves, R.C.; Oliveira, M.B.P.P. Amino Acid Profile and Protein Quality Assessment of Macroalgae Produced in an Integrated Multi-Trophic Aquaculture System. *Foods* **2020**, *9*, 1382. [CrossRef]
29. Syakilla, N.; George, R.; Chye, F.Y.; Pindi, W.; Mantihal, S.; Wahab, N.A.; Fadzwi, F.M.; Gu, P.H.; Matanjun, P. A Review on Nutrients, Phytochemicals, and Health Benefits of Green Seaweed, Caulerpa lentillifera. *Foods* **2022**, *11*, 2832. [CrossRef]
30. Circuncisão, A.R.; Catarino, M.D.; Cardoso, S.M.; Silva, A.M.S. Minerals from Macroalgae Origin: Health Benefits and Risks for Consumers. *Mar. Drugs* **2018**, *16*, 400. [CrossRef]
31. Arokiarajan, M.S.; Thirunavukkarasu, R.; Joseph, J.; Ekaterina, O.; Aruni, W. Advance research in biomedical applications on marine sulfated polysaccharide. *Int. J. Biol. Macromol.* **2022**, *194*, 870–881. [CrossRef]
32. MacArtain, P.; Christopher, I.R.; Brooks, G.M.; Campbell, R.; Rowland, I.R. Nutritional value of edible seaweeds. *Nutr. Rev.* **2007**, *65*, 535–543. [CrossRef] [PubMed]
33. Amico, V.; Piatelli, M.; Cunsolo, F.; Recupero, M.; Ruberto, G. Etraprenyltoluquinols as chemotaxonomic markers in the genus Cystoseira: C. barbarula and C. barbata, Gazz. *Chim. Ital.* **1990**, *12*, 9–12.
34. Li, B.; Lu, F.; Wei, X.; Zhao, R. Fucoidan: Structure and bioactivity. *Molecules* **2008**, *12*, 1671–1695. [CrossRef]
35. Pozharitskaya, O.N.; Shikov, A.N.; Faustova, N.M.; Obluchinskaya, E.D.; Kosman, V.M.; Vuorela, H.; Makarov, V.G. Pharmacokinetic and tissue distribution of fucoidan from Fucus vesiculosus after oral administration to rats. *Mar. Drugs* **2018**, *16*, 132. [CrossRef]
36. Krylova, N.V.; Ermakova, S.P.; Lavrov, V.F.; Leneva, I.A.; Kompanets, G.G.; Iunikhina, O.V.; Nosik, M.N.; Ebralidze, L.K.; Falynskova, I.N.; Silchenko, A.S.; et al. The comparative analysis of antiviral activity of native and modified fucoidans from brown algae Fucus evanescens in Vitro and in Vivo. *Mar. Drugs* **2020**, *18*, 224. [CrossRef]
37. Diogo, J.V.; Novo, S.G.; Gonzalez, M.J.; Ciancia, M.; Bratanich, A.C. Antiviral activity of lambda-carrageenan prepared from red seaweed (*Gigartina skottsbergii*) against BoHV-1 and SuHV-1. *Res. Vet. Sci.* **2015**, *98*, 142–144. [CrossRef]
38. Vairappan, C.S. Potent antibacterial activity of halogenated metabolites from Red algae Laurencia majuscule (Rhodomelaceae, Ceramiales). *Biomol. Eng.* **2003**, *20*, 255–259. [CrossRef] [PubMed]
39. Lee, J.Y.; Kim, Y.J.; Kim, H.J.; Kim, Y.S.; Park, W. Immunostimulatory effect of laminarin on RAW 264.7 mouse macrophages. *Molecules* **2012**, *17*, 5404–5411. [CrossRef] [PubMed]
40. Choi, J.I.; Kim, H.J.; Lee, J.W. Structural feature and antioxidant activity of low molecular weight laminarin degraded by gamma irradiation. *Food Chem.* **2011**, *129*, 520–523. [CrossRef] [PubMed]
41. Lagopati, N.; Pavlatou, E.A. Advanced Applications of Biomaterials Based on Alginic Acid. *Am. J. Biomed. Sci.* **2020**, *9*, 47–53. [CrossRef]
42. Cervino, G.; Fiorillo, L.; Herford, A.S.; Laino, L.; Troiano, G.; Amoroso, G.; Crimi, S.; Matarese, M.; D'Amico, C.; Nastro Siniscalchi, E.; et al. Alginate Materials and Dental Impression Technique: A Current State of the Art and Application to Dental Practice. *Mar. Drugs* **2018**, *17*, 18. [CrossRef]
43. Kaliampakou, C.; Lagopati, N.; Charitidis, C.A. Direct Ink Writing of Alginate–Gelatin Hydrogel: An Optimization of Ink Property Design and Printing Process Efficacy. *Appl. Sci.* **2023**, *13*, 8261. [CrossRef]
44. Kamran, S.; Sinniah, A.; Abdulghani, M.A.M.; Alshawsh, M.A. Therapeutic Potential of Certain Terpenoids as Anticancer Agents: A Scoping Review. *Cancers* **2022**, *14*, 1100. [CrossRef] [PubMed]
45. Hannan, M.A.; Sohag, A.A.M.; Dash, R.; Haque, M.N.; Mohibbullah, M.; Oktaviani, D.F.; Hossain, M.T.; Choi, H.J.; Moon, I.S. Phytosterols of marine algae: Insights into the potential health benefits and molecular pharmacology. *Phytomedicine* **2020**, *69*, 153201. [CrossRef] [PubMed]
46. Rossano, R.; Ungaro, N.; D'Ambrosio, A.; Liuzzi, G.M.; Riccio, P. Extracting and purifying R-phycoerythrin from Mediterranean red algae Corallina elongata Ellis & Solander. *J. Biotechnol.* **2003**, *101*, 289–293. [CrossRef] [PubMed]
47. Cardoso, S.; Carvalho, L.; Silva, P.; Rodrigues, M.; Pereira, O.; Pereira, L. Bioproducts from seaweeds: A review with special focus on the iberian peninsula. *Curr. Org. Chem.* **2014**, *18*, 896–917. [CrossRef]
48. Stévant, P.; Marfaing, H.; Duinker, A.; Fleurence, J.; Rustad, T.; Sandbakken, I.; Chapman, A. Biomass soaking treatments to reduce potentially undesirable compounds in the edible seaweeds sugar kelp (*Saccharina latissima*) and winged kelp (*Alaria esculenta*) and health risk estimation for human consumption. *J. Appl. Phycol.* **2018**, *30*, 2047–2060. [CrossRef]
49. Santos, C.P.G.; Prado, J.P.S.; Fernandes, K.R.; Kido, H.W.; Dorileo, B.P.; Parisi, J.R.; Silva, J.A.; Cruz, M.A.; Custódio, M.R.; Rennó, A.C.M.; et al. Different Species of Marine Sponges Diverge in Osteogenic Potential When Therapeutically Applied as Natural Scaffolds for Bone Regeneration in Rats. *J. Funct. Biomater.* **2023**, *14*, 122. [CrossRef] [PubMed]
50. Gatou, M.-A.; Lagopati, N.; Tsoukleris, D.; Pavlatou, E.A. Commercial Sponges as A Novel Technology for Crude Oil Removal from Seawater and Industrial Wastewater: A Review. *Biomed. J. Sci. Tech. Res.* **2020**, *25*, 19426–19436. [CrossRef]

51. Wan, M.C.; Qin, W.; Lei, C.; Li, Q.H.; Meng, M.; Fang, M.; Song, W.; Chen, J.H.; Tay, F.; Niu, L.N. Biomaterials from the sea: Future building blocks for biomedical applications. *Bioact. Mater.* **2021**, *6*, 4255–4285. [CrossRef]
52. Piel, J.; Hui, D.; Wen, G.; Butzke, D.; Platzer, M.; Fusetani, N.; Matsunaga, S. Antitumor polyketide biosynthesis by an uncultivated bacterial symbiont of the marine sponge Theonella swinhoei. *Proc. Natl. Acad. Sci. USA* **2004**, *101*, 16222–16227. [CrossRef] [PubMed]
53. de Silva, E.D.; Scheuer, P.J. Monoalide, an Antibiotic Sesterterpenoid from the MArine Sponge Luffariella variabilis. *Tetrahedron. Lett.* **1980**, *21*, 1611–1614. [CrossRef]
54. Ortiz, A.R.; Pisabarro, M.T.; Gago, F. Molecular Model of the Interaction of Bee Venom Phospholipase A2 with Manoalide. *J. Med. Chem.* **1993**, *36*, 1866–1879. [CrossRef] [PubMed]
55. Su, J.Y.; Meng, Y.H.; Zeng, L.M.; Stellettin, A. A New Triterpenoid Pigment from the MArine Sponge Stelletta tenuis. *J. Nat. Prod.* **1994**, *57*, 1450–1451. [CrossRef] [PubMed]
56. Ashok, P.; Ganguly, S.; Murugesan, S. Manzamine alkaloids: Isolation, cytotoxicity, antimalarial activity and SAR studies. *Drug Discov. Today* **2014**, *19*, 1781–1791. [CrossRef] [PubMed]
57. Negi, B.; Kumar, D.; Rawat, D.S. Marine Peptides as Anticancer Agents: A Remedy To Mankind By Nature. *Curr. Protein. Pept. Sci.* **2017**, *18*, 1–20. [CrossRef]
58. Gupta, P.; Sharma, U.; Schulz, T.C.; McLean, A.B.; Robins, A.J.; West, L.M. Bicyclic C21 terpenoids from the marine sponge Clathria compressa. *J. Nat. Prod.* **2012**, *75*, 1223–1227. [CrossRef]
59. Keffer, J.L.; Plaza, A.; Bewley, C.A. Motualevic Acids A–F, Antimicrobial Acids from the Sponge *Siliquariaspongia* sp. *Org. Lett.* **2009**, *11*, 1087–1090. [CrossRef]
60. Yamashita, A.; Tamaki, M.; Kasai, H.; Tanaka, T.; Otoguro, T.; Ryo, A.; Maekawa, S.; Enomoto, N.; de Voogd, N.J.; Tanaka, J.; et al. Inhibitory effects of metachromin A on hepatitis B virus production via impairment of the viral promoter activity. *Antiviral. Res.* **2017**, *145*, 136–145. [CrossRef]
61. Karpiński, T.M. Marine Macrolides with Antibacterial and/or Antifungal Activity. *Mar. Drugs* **2019**, *17*, 241. [CrossRef]
62. Zhou, R.; Liao, X.; Li, H.; Li, J.; Feng, P.; Zhao, B.; Xu, S. Isolation and Synthesis of Misszrtine A: A Novel Indole Alkaloid From Marine Sponge-Associated *Aspergillus* sp. SCSIO XWS03F03. *Front. Chem.* **2018**, *6*, 212. [CrossRef] [PubMed]
63. Shubina, L.K.; Makarieva, T.N.; Denisenko, V.A.; Popov, R.S.; Dyshlovoy, S.A.; Grebnev, B.B.; Dmitrenok, P.S.; von Amsberg, G.; Stonik, V.A. Gracilosulfates, A–G, Monosulfated Polyoxygenated Steroids from the Marine Sponge Haliclona gracilis. *Mar. Drugs* **2020**, *18*, 454. [CrossRef] [PubMed]
64. Nagabhishek, S.N.; Madankumar, A. A Novel Apoptosis-Inducing Metabolite Isolated from Marine Sponge Symbiont: *Monascus* sp. NMK7 Attenuates Cell Proliferation, Migration and ROS Stress-Mediated Apoptosis in Breast Cancer Cells. *RSC Adv.* **2019**, *9*, 5878–5890. [CrossRef] [PubMed]
65. Wang, X.; Schröder, H.C.; Wiens, M.; Schloßmacher, U.; Müller, W.E. Biosilica: Molecular Biology, Biochemistry and Function in Demosponges as well as its Applied Aspects for Tissue Engineering. *Adv. Mar. Biol.* **2012**, *62*, 231–271. [CrossRef]
66. Zobi, F. Diatom Biosilica in Targeted Drug Delivery and Biosensing Applications: Recent Studies. *Micro* **2022**, *2*, 342–360. [CrossRef]
67. Götz, W.; Tobiasch, E.; Witzleben, S.; Schulze, M. Effects of Silicon Compounds on Biomineralization, Osteogenesis, and Hard Tissue Formation. *Pharmaceutics* **2019**, *11*, 117. [CrossRef]
68. Lowe, B.; Venkatesan, J.; Anil, S.; Shim, M.S.; Kim, S.K. Preparation and characterization of chitosan-natural nano hydroxyapatite-fucoidan nanocomposites for bone tissue engineering. *Int. J. Biol. Macromol.* **2016**, *93 Pt B*, 1479–1487. [CrossRef]
69. Skaggs, D.L.; Samuelson, M.A.; Hale, J.M.; Kay, R.M.; Tolo, V.T. Complications of posterior iliac crest bone grafting in spine surgery in children. *Spine (Phila Pa 1976)* **2000**, *25*, 2400–2402. [CrossRef]
70. Tziveleka, L.A.; Ioannou, E.; Tsiourvas, D.; Berillis, P.; Foufa, E.; Roussis, V. Collagen from the Marine Sponges Axinella cannabina and Suberites carnosus: Isolation and Morphological, Biochemical, and Biophysical Characterization. *Mar. Drugs* **2017**, *15*, 152. [CrossRef]
71. Loh, Q.L.; Choong, C. Three-dimensional scaffolds for tissue engineering applications: Role of porosity and pore size. *Tissue Eng. Part B Rev.* **2013**, *19*, 485–502. [CrossRef]
72. Zdarta, J.; Norman, M.; Smułek, W.; Moszyński, D.; Kaczorek, E.; Stelling, A.L.; Ehrlich, H.; Jesionowski, T. Spongin-Based Scaffolds from Hippospongia communis Demosponge as an Effective Support for Lipase Immobilization. *Catalysts* **2017**, *7*, 147. [CrossRef]
73. Elieh-Ali-Komi, D.; Hamblin, M.R. Chitin and Chitosan: Production and Application of Versatile Biomedical Nanomaterials. *Int. J. Adv. Res.* **2016**, *4*, 411–427.
74. de Sousa Victor, R.; Marcelo da Cunha Santos, A.; Viana de Sousa, B.; de Araújo Neves, G.; Navarro de Lima Santana, L.; Rodrigues Menezes, R. A Review on Chitosan's Uses as Biomaterial: Tissue Engineering, Drug Delivery Systems and Cancer Treatment. *Materials* **2020**, *13*, 4995. [CrossRef] [PubMed]
75. Thambiliyagodage, C.; Jayanetti, M.; Mendis, A.; Ekanayake, G.; Liyanaarachchi, H.; Vigneswaran, S. Recent Advances in Chitosan-Based Applications—A Review. *Materials* **2023**, *16*, 2073. [CrossRef]
76. Guo, C.; Ling, S.; Li, C.; Motta, A.; Oliveira, J.M. Editorial: Silk-Based Functional Biomaterials. *Front. Bioeng. Biotechnol.* **2021**, mboxemph9, 721761. [CrossRef]
77. Luquet, G. Biomineralizations: Insights and prospects from crustaceans. *Zookeys* **2012**, *176*, 103–121. [CrossRef]

78. Kim, Y.; Zharkinbekov, Z.; Raziyeva, K.; Tabyldiyeva, L.; Berikova, K.; Zhumagul, D.; Temirkhanova, K.; Saparov, A. Chitosan-Based Biomaterials for Tissue Regeneration. *Pharmaceutics* **2023**, *15*, 807. [CrossRef] [PubMed]
79. Sethmann, I.; Luft, C.; Kleebe, H.-J. Development of Phosphatized Calcium Carbonate Biominerals as Bioactive Bone Graft Substitute Materials, Part I: Incorporation of Magnesium and Strontium Ions. *J. Funct. Biomater.* **2018**, *9*, 69. [CrossRef] [PubMed]
80. Silva, A.S.; Costa, E.C.; Reis, S.; Spencer, C.; Calhelha, R.C.; Miguel, S.P.; Ribeiro, M.P.; Barros, L.; Vaz, J.A.; Coutinho, P. Silk Sericin: A Promising Sustainable Biomaterial for Biomedical and Pharmaceutical Applications. *Polymers* **2022**, *14*, 4931. [CrossRef] [PubMed]
81. Vepari, C.; Kaplan, D.L. Silk as a Biomaterial. *Prog. Polym. Sci.* **2007**, *32*, 991–1007. [CrossRef]
82. Kim, J.S.; Choi, J.; Ki, C.S.; Lee, K.H. 3D Silk Fiber Construct Embedded Dual-Layer PEG Hydrogel for Articular Cartilage Repair—In vitro Assessment. *Front. Bioeng. Biotechnol.* **2021**, *9*, 653509. [CrossRef]
83. Yu, L.M.; Liu, T.; Ma, Y.L.; Zhang, F.; Huang, Y.C.; Fan, Z.H. Fabrication of Silk-Hyaluronan Composite as a Potential Scaffold for Tissue Repair. *Front. Bioeng. Biotechnol.* **2020**, *8*, 578988. [CrossRef]
84. Tanaka, T.; Abe, Y.; Cheng, C.J.; Tanaka, R.; Naito, A.; Asakura, T. Development of Small-Diameter Elastin-Silk Fibroin Vascular Grafts. *Front. Bioeng. Biotechnol.* **2021**, *8*, 622220. [CrossRef] [PubMed]
85. Zhou, L.; Pan, M.; Zhang, Z.; Diao, Z.; Peng, X. Enhancing Osseointegration of TC4 Alloy by Surficial Activation Through Biomineralization Method. *Front. Bioeng. Biotechnol.* **2021**, *9*, 639835. [CrossRef] [PubMed]
86. Kakui, K.; Fleming, J.F.; Mori, M.; Fujiwara, Y.; Arakawa, K. Comprehensive Transcriptome Sequencing of Tanaidacea with Proteomic Evidences for Their Silk. *Genome. Biol. Evol. (GBE)* **2021**, *13*, evab281. [CrossRef] [PubMed]
87. Siddiqui, H.A.; Pickering, K.L.; Mucalo, M.R. A Review on the Use of Hydroxyapatite-Carbonaceous Structure Composites in Bone Replacement Materials for Strengthening Purposes. *Materials* **2018**, *11*, 1813. [CrossRef]
88. Radulescu, D.-E.; Neacsu, I.A.; Grumezescu, A.-M.; Andronescu, E. Novel Trends into the Development of Natural Hydroxyapatite-Based Polymeric Composites for Bone Tissue Engineering. *Polymers* **2022**, *14*, 899. [CrossRef]
89. Chen, L.; Al-Bayatee, S.; Khurshid, Z.; Shavandi, A.; Brunton, P.; Ratnayake, J. Hydroxyapatite in Oral Care Products-A Review. *Materials* **2021**, *14*, 4865. [CrossRef]
90. Lueyot, A.; Rungsardthong, V.; Vatanyoopaisarn, S.; Hutangura, P.; Wonganu, B.; Wongsa-Ngasri, P.; Charoenlappanit, S.; Roytrakul, S.; Thumthanaruk, B. Influence of collagen and some proteins on gel properties of jellyfish gelatin. *PLoS ONE* **2021**, *16*, e0253254. [CrossRef]
91. Naomi, R.; Bahari, H.; Ridzuan, P.M.; Othman, F. Natural-Based Biomaterial for Skin Wound Healing (Gelatin vs. Collagen): Expert Review. *Polymers* **2021**, *13*, 2319. [CrossRef]
92. Al-Nimry, S.; Dayah, A.A.; Hasan, I.; Daghmash, R. Cosmetic, Biomedical and Pharmaceutical Applications of Fish Gelatin/Hydrolysates. *Mar. Drugs* **2021**, *19*, 145. [CrossRef] [PubMed]
93. Alemán, A.; Pérez-Santín, E.; Bordenave-Juchereau, S.; Arnaudin, I.; Gómez-Guillén, M.; Montero, P. Squid Gelatin Hydrolysates with Antihypertensive, Anticancer and Antioxidant Activity. *Food Res. Int.* **2011**, *44*, 1044–1051. [CrossRef]
94. Lv, L.C.; Huang, Q.Y.; Ding, W.; Xiao, X.H.; Zhang, H.Y.; Xiong, L.X. Fish Gelatin: The Novel Potential Applications. *J. Funct. Foods* **2019**, *63*, 103581103594. [CrossRef]

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