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Sustainable Seafood Processing: Reducing Waste and Environmental Impact in Aquatic Ecosystems

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ABSTRACT

The global seafood industry is crucial in food production, providing essential nutrition and contributing to food security. Beyond its traditional role, the industry holds significant potential for generating high-value products by utilizing seafood resources. This comprehensive review explores the diverse applications of seafood resources, focusing on fish, shellfish, and seaweeds, in producing high-value products. The review examines various technological processes in extracting and purifying bioactive compounds from seafood, highlighting the advancements in seafood processing areas such as nanoencapsulation, fermentation, and enzymatic hydrolysis. Furthermore, it also discusses these innovations' economic and environmental impacts, emphasizing the importance of sustainability and efficiency in utilizing seafood by-products and waste. The seafood industry can minimize environmental pollution and promote circular economy principles by repurposing these materials. The review provides a holistic view of the future directions in this field, advocating for continued research and development efforts to enhance the value and sustainability of seafood resources. Overall, this review underscores the significance of seafood-derived high-value products in addressing global challenges while fostering economic growth and environmental stewardship.

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1 Introduction

Seafood, encompassing a diverse range of marine organisms such as fish, shellfish, and seaweeds, has long been integral to human diets globally (Luo et al. 2024; Martins et al. 2024). Its appeal lies in its delicious taste and exceptional nutritional value, offering essential nutrients like high-quality proteins, omega-3 fatty acids, vitamins, and minerals crucial for maintaining overall health (Tas and El 2024; Edo et al. 2024). With the global population steadily increasing, the demand for nutritious food sources is rising, prompting the seafood industry to explore innovative methods to utilize seafood resources efficiently and sustainably (Dhandwal et al. 2024). This exploration is pivotal for enhancing food security, reducing waste, and adding economic value to the industry.

The significance of seafood in global food security cannot be overstated. It serves as a primary source of animal protein for over three billion people worldwide and significantly contributes to the livelihoods of millions, particularly in coastal communities. Fish alone provides approximately 17% of the global animal protein intake and is a vital part of traditional diets in many cultures (Magbanua and Ragaza 2024). Seafood's rich nutrient profile, particularly its high content of omega-3 fatty acids, is associated with numerous health benefits, including improved cardiovascular health, enhanced cognitive function, and reduced inflammation (Tacon et al. 2024).

Further, seafood is a rich source of bioactive compounds such as omega-3 fatty acids, peptides, collagen, and chitin, which have significant health benefits and are used in formulating dietary supplements, functional foods, and therapeutic products. For instance, fish oils rich in omega-3 fatty acids are marketed as supplements for heart health, while peptides derived from fish proteins are explored for their antihypertensive and antioxidant properties (Santos et al. 2020. The cosmetic industry also benefits from marine-derived ingredients like collagen and alginates, which are prized for their skin health benefits (Kalasariya et al. 2024). Collagen from fish skin is used in anti-aging creams and other skincare products.

The rising demand for seafood has led to overfishing and the depletion of many fish stocks, raising concern about the long-term sustainability of marine resources. This scenario necessitates a paradigm shift towards more sustainable seafood production and utilization practices. One promising approach is producing high-value products from seafood resources (Cadena et al. 2024) (Figure 1). These products extend beyond traditional food consumption, including nutraceuticals, pharmaceuticals, cosmetics, and industrial products (Zhang et al. 2024). They are often derived from parts of seafood that are typically considered waste, such as fish skin, bones, viscera, shellfish exoskeletons, and seaweed biomass (Naghdi et al. 2024). Beyond health and beauty, seafood resources are also utilized in various industrial applications. Chitosan, derived from chitin in shellfish shells, is used in water treatment, bioplastics, and as a food preservative due to its biodegradable and non-toxic properties (Venugopal 2022). Additionally, seaweed biomass is explored for biofuel production, offering a renewable energy source that can help reduce reliance on fossil fuels (Milledge et al. 2014). One key strategy for enhancing the value derived from seafood resources is the utilization of by-products and waste. The seafood processing industry generates substantial by-products, which, if not properly managed, can lead to environmental pollution. However, these by-products are often rich in valuable compounds that can be extracted and utilized in high-value applications. For example, fish processing generates by-products such as heads, frames, skin, and viscera, which can be processed into fish protein hydrolysates, fish oil, and collagen (Välimaa et al. 2019). Similarly, shellfish shells can be a source of chitin and chitosan, and seaweed trimmings can extract bioactive polysaccharides like alginates and carrageenan.

The efficient extraction and utilization of high-value products from seafood resources require advanced technological processes. Techniques such as supercritical fluid extraction, enzymatic hydrolysis, and membrane filtration are employed to isolate and purify bioactive compounds from seafood by-products (Bruno et al. 2019). These technologies enhance the yield and quality of the extracted products and ensure that the processes are environmentally sustainable. Moreover, biotechnological advancements, including fermentation and genetic modification, are being explored to improve the efficiency and functionality of seafood-derived products. For instance, fermentation processes can enhance the bioavailability and health benefits of bioactive compounds, while genetic modification can increase the production of desirable compounds in marine organisms.

The shift towards producing high-value products from seafood resources offers significant economic and environmental benefits (Veríssimo et al. 2021). Economically, it opens up new markets and revenue streams for the seafood industry, creating job opportunities and stimulating economic growth, especially in coastal and rural areas (Burbridge et al. 2021). Environmentally, it promotes sustainability by reducing waste and minimizing the ecological footprint of seafood processing activities. This approach aligns with the principles of a circular economy, where resources are used efficiently and waste is transformed into valuable products. Despite the promising potential, several challenges must be addressed to fully realize the benefits of utilizing seafood resources for high-value products (Cooney et al. 2023). These include ensuring sustainable harvesting practices, developing cost-effective and scalable extraction technologies, and establishing regulatory frameworks to ensure the safety and efficacy of seafood-derived products. Additionally, consumer acceptance and market development for these products are crucial for their

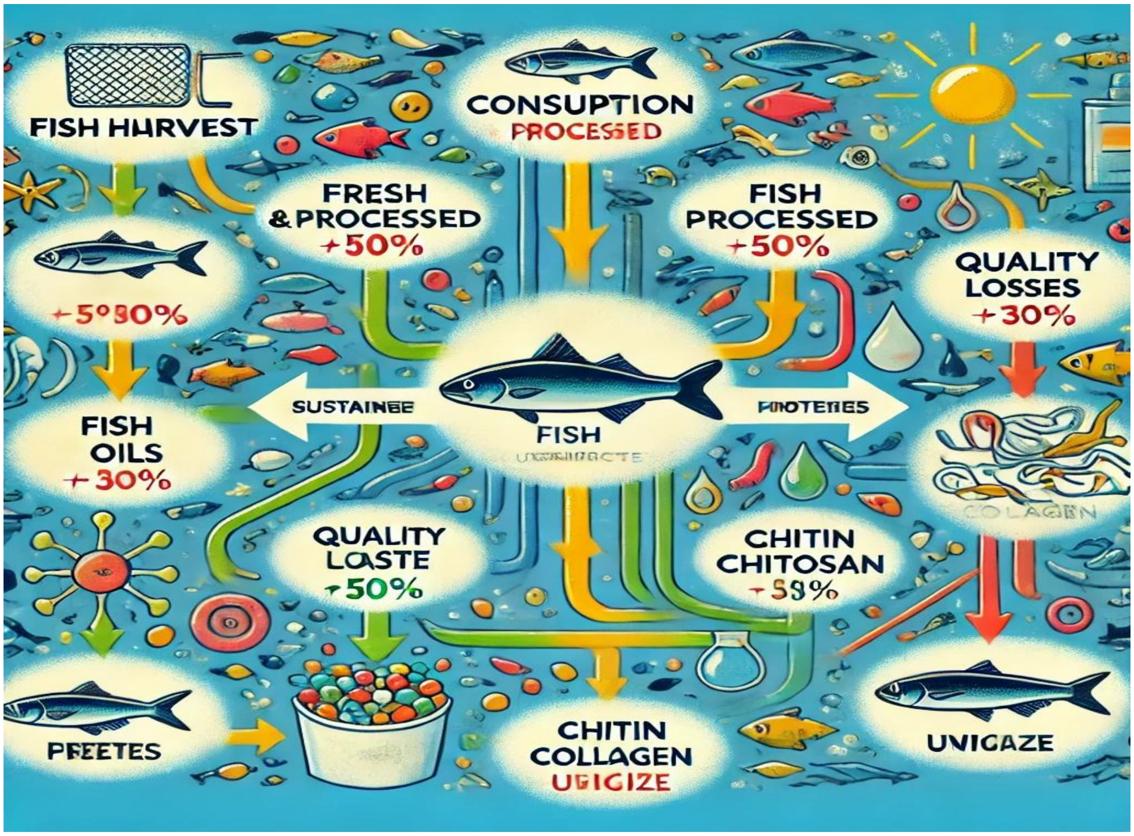

Figure 1 Seafood product description

successful commercialization. This review article aims to conduct an in-depth analysis of sustainable seafood processing practices, focusing on reducing waste and minimizing the environmental impact on aquatic ecosystems. The study seeks to identify innovative methods that transform fish by-products, traditionally discarded as waste, into valuable resources such as fish oils, proteins, enzymes, and collagen. By improving the efficiency of seafood processing, the research aims to maximize the use of harvested fish while significantly reducing the volume of waste generated. Additionally, the study aims to assess the current challenges related to quality and safety losses during seafood processing, which can lead to environmental harm and economic inefficiencies. By exploring advanced technological solutions, such as precision processing techniques, water recycling systems, and closed-loop operations, the research seeks to develop methods that address these issues while lowering the carbon footprint of the seafood industry. A core objective is to investigate how integrating sustainable practices, such as using renewable energy and eco-friendly packaging materials, can further reduce the environmental burden associated with seafood processing. The study will also emphasize the importance of responsible sourcing and traceability systems to promote sustainable fishing practices and ensure the long-term health of marine ecosystems. Ultimately, the study also provides practical recommendations for the seafood industry to adopt more sustainable processing methods, contributing to conserving marine biodiversity, protecting aquatic ecosystems, and achieving global food security. Through these efforts, the research aspires to align industry practices with environmental sustainability and the responsible management of marine resources.

2 Importance of seafood in global food security

The efficient use of seafood resources can enhance food security, reduce waste, and contribute to economic growth, particularly in coastal communities reliant on fishing industries (Farmery et al., 2022). Seafood plays a crucial role in global food security, serving as a primary source of protein for billions of people worldwide. Omega-3 fatty acids, for instance, are known for their benefits to cardiovascular health and cognitive function, while the vitamins and minerals found in seafood contribute to various bodily functions, including bone health and immune support (Stetkiewicz et al. 2022). Efficient utilization of seafood resources is important for nutritional, economic, and environmental reasons. By optimizing these resources, we can enhance food security by ensuring a steady and sustainable supply of nutrient-rich food. Reducing waste through better resource management can also bring significant economic benefits, especially in coastal communities that depend heavily on fishing industries.

3 Overview of high-value products from seafood

3.1 Bioactive compounds

High-value products derived from seafood include a variety of bioactive compounds that offer significant health and economic benefits. Omega-3 fatty acids, primarily found in fish oils, are one of the most well-known bioactive compounds. These essential fatty acids, particularly EPA and DHA, are crucial for maintaining cardiovascular health, supporting brain function, and reducing inflammation. Omega-3 supplements are widely consumed globally due to their proven benefits in reducing the risk of heart disease and improving mental health outcomes (Ozogul et al. 2021). Peptides derived from seafood are another valuable bioactive compound. These short chains of amino acids, obtained through the hydrolysis of fish proteins, possess various health-promoting properties. They have been shown to exhibit antioxidant, antihypertensive, and antimicrobial activities. Due to these properties, fish-derived peptides are increasingly used in functional foods and nutraceuticals to enhance health and wellbeing (Mutalipassi et al. 2021).

The health and beauty industries extensively utilize collagen extracted from fish skin, bones, and scales. Marine collagen is prized for its high bioavailability and efficacy in improving skin health, reducing wrinkles, and promoting joint health. Its applications in cosmetic products such as creams, serums, and supplements have made it a popular ingredient for maintaining youthful skin and overall physical vitality (Menon and Lele 2015).

Chitin and its derivative, chitosan, are extracted from the exoskeletons of shellfish like shrimp and crabs. These compounds are renowned for their versatility and functional properties and are used in various applications, including biomedical fields for wound healing and drug delivery systems, due to their biocompatibility and biodegradability (Hamed et al. 2016). They are also used in agricultural products, water treatment processes, and as natural preservatives in food products.

3.2 Pharmaceuticals and nutraceuticals

Seafood is a rich bioactive compound source that has garnered attention for their potential pharmaceutical and nutraceutical applications (Ashraf et al. 2020). Seafood-derived antioxidants, such as astaxanthin in shrimp and krill, exhibit potent antioxidant properties, making them valuable ingredients in pharmaceutical formulations and dietary supplements to promote overall health and wellbeing (Ashraf et al. 2020).

Furthermore, seafood is a reservoir of anti-inflammatory agents, which have been studied for their therapeutic potential in managing inflammatory conditions such as arthritis, inflammatory bowel disease, and asthma (D'Orazio et al. 2012). Compounds like omega-3 fatty acids, particularly EPA and DHA found in fish oils, possess anti-inflammatory properties that can help alleviate symptoms and reduce the severity of inflammatory diseases (D'Orazio et al. 2012). As a result, fish oil supplements have become increasingly popular as adjunctive therapy in managing inflammatory disorders.

Dietary supplements derived from seafood offer a convenient and effective means of delivering essential nutrients and bioactive compounds to consumers (Awuchi et al. 2022). These supplements may include fish oil capsules rich in omega-3 fatty acids, krill oil supplements containing astaxanthin and phospholipids, and collagen supplements derived from fish skin and bones. These products are marketed for various health benefits, including cardiovascular support, joint health, cognitive function, and skin rejuvenation. In addition to traditional pharmaceuticals and nutraceuticals, seafood-derived compounds are being investigated for their potential therapeutic applications in areas such as cancer treatment, wound healing, and immune modulation (Mutalipassi et al. 2021). The unique composition of bioactive compounds found in seafood presents exciting opportunities for developing novel pharmaceuticals and nutraceuticals that can address unmet medical needs and improve health outcomes for individuals worldwide. As research in this field advances, seafood is poised to play an increasingly important role in developing innovative therapies and preventive healthcare solutions.

3.3 Cosmetics

The cosmetics industry has long recognized the potential of marine-derived compounds for enhancing skin health and beauty. Seafood is a rich bioactive compound source that offers various benefits when incorporated into cosmetic formulations (Siahaan et al. 2022). One of the most sought-after ingredients is marine-derived collagen, extracted from fish's skin, bones, and scales. Marine collagen is prized for its high bioavailability and compatibility with human skin, making it an ideal ingredient for anti-aging skincare products. Collagen helps improve skin elasticity, reduce the appearance of wrinkles and fine lines, and promote overall skin hydration, resulting in a more youthful and radiant complexion (Mohiuddin 2019).

Alginates, derived from seaweed, are another valuable ingredient in cosmetics. These polysaccharides have unique gelling and hydrating properties, making them ideal for skincare products such as masks, creams, and serums (Pereira 2018). Alginate-based formulations help moisturize and soothe the skin, leaving it feeling soft, smooth, and refreshed. Additionally, alginates have been shown to have detoxifying and purifying effects, making them popular in skincare treatments designed to cleanse and rejuvenate the skin (López-Hortas et al. 2021). Other bioactive compounds found in seafood, such as astaxanthin and polyphenols, are also gaining attention in the cosmetics industry for their antioxidant properties (Fernandes et al. 2019). Astaxanthin, a carotenoid pigment found in shrimp, crab, and salmon, is one of the most powerful antioxidants, neutralizing free radicals and protecting the skin from oxidative damage caused by environmental stressors such as UV radiation and pollution. Astaxanthin-based skincare products help improve skin tone, reduce hyperpigmentation, and enhance overall skin resilience, providing a natural defence against premature aging (Fernandes et al. 2019). Incorporating marine-derived bioactive compounds into cosmetics offers consumers a natural and sustainable alternative to traditional skincare ingredients (Fernandes et al. 2019). By harnessing the power of the ocean, cosmetics companies can develop innovative formulations that deliver tangible results while minimizing environmental impact. As consumer demand for clean, eco-friendly beauty products continues to rise, marine-derived cosmetics are poised to become increasingly popular in the global market.

3.4 Industrial applications

Seafood resources are valuable for human consumption and cosmetic purposes and hold immense potential for various industrial applications (Figure 2). These applications include the production of biofuels, bioplastics, and enzymes, offering sustainable alternatives to conventional materials and processes (Singh et al. 2022).

Biofuels derived from seafood biomass, particularly seaweeds, are gaining attention as renewable energy sources. Seaweeds have a high growth rate and can be cultivated using minimal land and freshwater resources, making them an attractive option for biofuel production. Additionally, seaweeds do not compete with food crops for agricultural land, mitigating concerns about food security and land use conflicts. Through processes such as fermentation and anaerobic digestion, seaweed biomass can be converted into biofuels like bioethanol and biogas, which can be used to power vehicles, generate electricity, and heat homes, reducing reliance on fossil fuels and mitigating greenhouse gas emissions (Maneein et al. 2018).

Bioplastics made from seafood-derived compounds offer a sustainable alternative to petroleum-based plastics. Chitosan, a polysaccharide derived from chitin found in shellfish shells, is one such compound that has garnered interest for its biodegradability, biocompatibility, and antimicrobial properties. Chitosan-based bioplastics have applications in packaging, agriculture, and biomedical fields, providing an eco-friendly solution to plastic pollution and environmental degradation. By replacing

Figure 2 Seafood industrial application overview

conventional plastics with biodegradable alternatives, seafood-derived bioplastics contribute to efforts to reduce plastic waste and promote a circular economy (Maneein et al. 2018).

Enzymes extracted from seafood organisms are valuable catalysts for various industrial processes. These enzymes exhibit unique properties such as high specificity, stability, and activity under extreme conditions, making them suitable for food processing, textile manufacturing, and wastewater treatment applications. For example, proteases and lipases from marine organisms are used in detergent formulations to enhance stain removal and fabric softening. Additionally, enzymes like cellulases and amylases are employed in biofuel production to break down biomass into fermentable sugars, increasing yield and efficiency (Maneein et al. 2018).

In summary, seafood resources offer numerous opportunities for industrial innovation and sustainability. By harnessing the biochemical properties of marine organisms, we can develop renewable energy sources, eco-friendly materials, and efficient biotechnological processes that contribute to a greener and more sustainable future. As research in this field continues to advance, seafood-derived industrial applications have the potential to revolutionize various sectors and drive positive environmental and economic outcomes.

4 Utilization of seafood resources

4.1 Application of Fish Resources

4.1.1 Fish oil

Fish is one of the most extensively utilized seafood resources globally, with applications beyond direct consumption. Various parts of the fish, such as skin, bones, and viscera, traditionally discarded as waste, are now repurposed into high-value products. Among these, fish oils stand out for their rich content of omega-3 fatty acids, particularly eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA). These essential fatty acids are widely recognized for their health benefits, especially in cardiovascular, cognitive, and anti-inflammatory functions. The oils are primarily extracted from fatty fish species such as salmon, mackerel, and sardines, rich sources of these bioactive compounds.

In the commercial sector, fish oils are a key component of dietary supplements and functional foods that promote heart health and brain function. The growing awareness of omega-3's health benefits has led to a significant increase in the demand for fish oil supplements in the nutraceutical industry. Advanced extraction techniques, such as supercritical fluid extraction and molecular distillation, have been developed to enhance these oils' yield, purity, and stability, ensuring their high quality for commercial use. These technologies also reduce contaminants, such as heavy metals and pollutants, further enhancing product safety. In addition to human health, fish oils are also used in aquaculture feed to improve the nutritional profile of farmed fish, thereby contributing to the sustainability of fish farming practices. The wide-ranging commercial applications of fish oils underscore their importance as a by-product of sustainable seafood processing practices.

4.1.2 Collagen and gelatin

Collagen and gelatin, derived from fish skin, scales, and bones, have gained significant commercial importance in various industries, including food, cosmetics, and pharmaceuticals. Collagen, a fibrous protein, is widely used for its health benefits, particularly in promoting skin elasticity, joint function, and wound healing. Gelatin, derived from the hydrolysis of collagen, is utilized as a gelling agent in food products, pharmaceuticals, and supplements. Fish-derived collagen has become an alternative to bovine or porcine sources due to its lower allergenicity and religious acceptability. The enzymatic hydrolysis process allows the production of collagen peptides, which are bioactive and easily absorbed by the body, making them a valuable ingredient in anti-aging and nutraceutical products. Additionally, collagen and gelatin have applications in regenerative medicine, such as in wound dressings and tissue scaffolding.

4.1.3 Fish protein hydrolysate

Fish protein hydrolysate (FPH) is produced by breaking fish proteins into smaller peptides through enzymatic hydrolysis, making it highly digestible and bioavailable. FPH has gained significant attention for its wide applications in the food, nutraceutical, and pharmaceutical industries. Due to its high nutritional value, FPH is commonly used as a functional ingredient in food products, offering emulsifying, foaming, and antioxidant properties. The peptides derived from FPH can also be bioactive compounds, exhibiting various health benefits such as antihypertensive, antimicrobial, and antioxidant activities. In the commercial market, FPH is incorporated into dietary supplements and specialized food products aimed at improving human health. It is particularly valuable in medical nutrition, where patients with compromised digestive systems require easily digestible proteins. Moreover, FPH is used in animal feed, especially aquaculture, to enhance farmed fish and shrimp's growth and immune response. The production of FPH also contributes to the sustainability of the seafood industry by utilizing fish by-products, which would otherwise be discarded as waste. Technological advances in the production of FPH have enabled better control of the degree of hydrolysis, allowing manufacturers to tailor the functional properties of the hydrolysates for specific applications. As the demand for sustainable, protein-rich ingredients grows, FPH remains a promising human and animal nutrition resource.

4.1.4 Bioactive Peptides

Bioactive peptides, derived from fish proteins, have emerged as valuable compounds in the nutraceutical and functional food industries due to their numerous health benefits. These short chains of amino acids exhibit various biological activities, including antioxidant, antimicrobial, antihypertensive, and anti-inflammatory properties. Bioactive peptides are produced through the enzymatic hydrolysis of fish proteins and have been shown to play a significant role in preventing and managing chronic diseases such as hypertension, cardiovascular disease, and diabetes (Power et al. 2013). Their ability to inhibit enzymes like angiotensin-converting enzyme (ACE) makes them potent antihypertensive agents. In the commercial sector, bioactive peptides are integrated into dietary supplements, functional foods, and beverages to enhance health and wellness. Additionally, they are being studied for their potential in cosmetic formulations for skin protection and anti-aging properties. The growing interest in bioactive peptides reflects their promising role as natural alternatives to synthetic compounds, with increasing applications in medical nutrition, particularly for aging populations. Advances in extraction and purification techniques, such as membrane filtration and chromatography, have improved the bioavailability and functionality of these peptides, further expanding their industrial use.

4.2 Utilization of shellfish resources

Shellfish, including shrimp, crab, and molluscs, are rich in bioactive compounds and chitin, which can be converted into high-value products (Azelee et al. 2023). The global shellfish industry generates large amounts of waste, primarily in exoskeletons and shells, rich in chitin, a biopolymer that can be converted into high-value products. Shellfish by-products are increasingly used in pharmaceuticals, food, and agriculture due to their bioactive compounds, which exhibit antioxidant, antimicrobial, and anti-inflammatory activities. These compounds are also used in cosmetics, contributing to anti-aging and skin health formulations. The commercial utilization of shellfish by-products helps to promote sustainability within the seafood industry by reducing waste and creating value-added products. In the food industry, shellfish-derived bioactive compounds are incorporated into functional foods, while in agriculture, they are used as biopesticides and soil conditioners. Additionally, the shellfish industry contributes to medical research, where bioactive compounds are being explored for their potential in drug development and wound healing applications (Islam et al. 2023). Recent innovations in processing and extraction technologies have further expanded the possibilities for utilizing shellfish by-products.

4.2.1 Chitin and chitosan

Chitin, a natural biopolymer found in the exoskeletons of crustaceans like shrimp and crabs, is one of the most abundant biopolymers on earth. Chitin is converted into chitosan, a highly versatile compound with various industrial applications through deacetylation. Chitosan's biocompatibility, biodegradability, and antimicrobial properties make it a valuable material in the biomedical field, where it is used in wound dressings, drug delivery systems, and tissue engineering. Chitosan's ability to form films and gels makes it an ideal candidate for water purification, agriculture, and food preservation (Azelee et al. 2023).

Commercially, chitosan is utilized in food packaging to extend shelf life by inhibiting microbial growth and in cosmetics for its skin-protective properties. In agriculture, chitosan is used as a natural pesticide and a plant growth enhancer. Its ability to form a protective barrier against pathogens has led to its use in biopesticides and seed coatings. The increasing demand for environmentally friendly and biodegradable materials has driven the growth of the chitosan industry, with ongoing research into new applications across various sectors, from pharmaceuticals to environmental management (Azelee et al. 2023; Akram et al., 2023).

4.2.2 Biomedical applications of chitosan

Chitosan is widely used in wound dressings for its unique properties that enhance wound healing. Its antimicrobial nature helps prevent infections, a critical aspect of wound management. Chitosan promotes hemostasis by aiding blood clotting, which is particularly beneficial for treating acute wounds. Furthermore, it facilitates the regeneration of tissues by providing a moist environment that supports cell proliferation and migration (Kankariya and Chatterjee 2023). Chitosan-based wound dressings are available in various forms, including films, hydrogels, and sponges, catering to different types of wounds and stages of healing. Chitosan plays a significant role in drug delivery due to its ability to form hydrogels, nanoparticles, and microspheres, which can encapsulate drugs and control their release. The biocompatibility and mucoadhesive properties of chitosan enhance the bioavailability of drugs, particularly those administered orally or through mucosal routes. Chitosan can be chemically modified to alter its solubility and degradation rate, providing customized drug delivery profiles (Haider et al. 2024). This makes chitosan an excellent carrier for many pharmaceuticals, including peptides, proteins, and vaccines, ensuring sustained and targeted drug release while minimizing side effects. Chitosan is extensively used in tissue engineering to develop scaffolds that mimic the extracellular matrix, supporting cell adhesion, proliferation, and differentiation (Wang et al. 2023). Its structural similarity to glycosaminoglycans, a component of the natural extracellular matrix, allows it to interact positively with cells and tissues. Chitosan scaffolds can be tailored to porosity, mechanical strength, and degradation rate to suit specific tissue engineering applications, such as bone, cartilage, skin, and nerve regeneration. Additionally, chitosan can be combined with other biomaterials like collagen or hydroxyapatite to enhance its functionality and performance in tissue repair and regeneration (Xing et al. 2023).

4.2.3 Agricultural applications of chitosan

Chitosan is widely recognized as an effective biopesticide in agriculture. Its natural antimicrobial properties help protect plants from various pathogens, including bacteria, fungi, and viruses. When applied to crops, chitosan can induce a plant's defence mechanisms, known as systemic acquired resistance (SAR), enhancing the plant's ability to resist infections. Chitosan disrupts the cell walls of pathogens, inhibiting their growth and spread (Román-Doval et al. 2023). Unlike chemical pesticides, chitosan is non-toxic and biodegradable, making it an environmentally friendly alternative that reduces the chemical load on the ecosystem and helps maintain soil health and biodiversity (Román-Doval et al. 2023).

In addition to its role as a biopesticide, chitosan also acts as a potent plant growth enhancer. It promotes seed germination and improves root development, leading to stronger and more resilient plants (Sun et al. 2023). Chitosan enhances plant nutrient uptake, ensuring better growth and higher yields. Its application can increase chlorophyll production, improving photosynthesis and overall plant vigour. Moreover, chitosan can stimulate the production of phytohormones such as auxins and gibberellins, which play crucial roles in plant growth and development (Islam et al. 2023). This multifaceted action of chitosan helps farmers achieve higher productivity and better-quality crops.

4.2.4 Water treatment applications of chitosan

Chitosan is highly effective in removing heavy metals from wastewater due to its excellent chelating properties. The amino groups in chitosan's structure can bind with metal ions such as lead, mercury, cadmium, and arsenic, forming stable complexes easily separated from the water. This process helps detoxify industrial effluents and prevent harmful metals' release into natural water bodies. The efficiency of chitosan in heavy metal removal can be enhanced by modifying its structure or combining it with other materials, making it a versatile and powerful tool in water purification (Bhatt et al. 2023).

In addition to heavy metals, chitosan removes dyes from wastewater, particularly from textile and dyeing industries. Dyes are often toxic and resistant to degradation, posing significant environmental hazards. Chitosan's adsorption capacity effectively captures and removes various dyes, including acidic, basic, and reactive dyes (Bhatt et al. 2023). The adsorption process involves electrostatic interactions, hydrogen bonding, and van der Waals forces between chitosan and the dye molecules. Chitosan can be used in different forms, such as beads, flakes, or membranes, to treat dye-laden wastewater efficiently (Bhatt et al. 2023).

4.2.5 Other bioactive compounds from shellfish

Shellfish, such as shrimp and crabs, are rich in bioactive compounds, with astaxanthin being one of the most notable. Astaxanthin is a powerful antioxidant found in the shells of these marine creatures, known for its exceptional ability to neutralize free radicals and protect cells from oxidative damage. This compound is widely utilized in various industries due to its health benefits and functional properties (Khursheed et al. 2023). In the nutraceutical sector, astaxanthin is incorporated into dietary supplements to support cardiovascular health, enhance immune function, and reduce inflammation. Its skin-protective and anti-aging properties make it a valuable ingredient in the cosmetics industry, where it is used in skincare products to improve skin elasticity, reduce wrinkles, and protect against UV damage (Khursheed et al. 2023). Additionally, astaxanthin's vibrant red-orange color makes it an attractive natural food colorant, enhancing the appearance of food products and imparting antioxidant benefits. These diverse applications highlight the significance of astaxanthin as a multifunctional bioactive compound derived from shellfish.

4.2.6 Shellfish-derived proteins and enzymes

Due to their functional and bioactive properties, shellfish-derived proteins and enzymes play crucial roles in various industries. Enzymes such as proteases and lipases extracted from shellfish are extensively used in food processing to enhance food products' texture, flavor, and nutritional value. These enzymes help break down proteins and fats, facilitating the creation of specialized products like tenderized meats and improved dairy items (Yang et al. 2023). In bioremediation, shellfish enzymes contribute to the degradation of pollutants, offering an environmentally friendly solution for cleaning up contaminated sites. Additionally, producing bioactive peptides from shellfish proteins has gained attention for their health benefits, including antihypertensive, antioxidant, and antimicrobial properties (Azelee et al. 2023). These peptides are incorporated into functional foods and nutraceuticals to promote health and wellness, demonstrating the diverse and significant applications of shellfish-derived proteins and enzymes across multiple sectors (Yang et al. 2023).

4.3 Utilization of seaweed resources

Seaweeds, also known as marine macroalgae, hold immense promise as a renewable resource that yields valuable products across multiple industries. Their abundant presence in marine ecosystems and rapid growth rates make them highly sustainable sources of raw materials. Seaweeds offer a rich biochemical composition, containing essential nutrients, vitamins, minerals, and bioactive compounds. This diverse array of compounds opens up numerous avenues for their utilization in producing high-value products (Jiménez-González et al. 2023). From food and nutritional supplements to pharmaceuticals, cosmetics, agricultural biostimulants, and even industrial materials like biofuels and bioplastics, seaweeds are being increasingly recognized for their versatility and potential (Jiménez-González et al. 2023).

4.3.1 Alginates, agar, and carrageenan

Seaweeds serve as a primary source of hydrocolloids, including alginates, agar, carrageenan, and polysaccharides, and they have diverse applications across several industries (Lomartire and Gonçalves 2023). In the food industry, these hydrocolloids act as essential additives, as thickeners, stabilizers, and gelling agents. Alginates, primarily extracted from brown seaweeds, are valued for their ability to form gels in the presence of calcium ions, making them ideal for use in products like dairy desserts, sauces, and bakery fillings (Lomartire and Gonçalves 2023). Agar, also derived from red seaweeds, forms strong and stable gels at relatively low concentrations, making it suitable for confectionery, desserts, and microbiological culture media applications. Carrageenan, obtained from red seaweeds, is widely used for its gelling, thickening, and stabilizing properties in various food products, including dairy, meat, and processed foods. Beyond the food industry, these seaweed-derived hydrocolloids find applications in pharmaceuticals, where they are utilized as excipients and drug delivery systems, and in cosmetics, where they serve as thickeners, emulsifiers, and moisturizers in various formulations (Lomartire and Gonçalves 2023). The versatility and functionality of alginates, agar, and carrageenan highlight the importance of seaweeds as valuable sources of hydrocolloids with widespread industrial applications.

4.3.2 Bioactive compounds from seaweeds

Seaweeds contain bioactive compounds like phycocyanins and fucoidans, known for their antioxidant, anti-inflammatory, and anticancer properties, contributing to their potential applications in pharmaceuticals, functional foods, and nutraceuticals.

4.3.2.1 Phlorotannins

Seaweeds are reservoirs of bioactive compounds, among which phlorotannins stand out for their remarkable antioxidant properties. These polyphenolic compounds are found abundantly in various species of seaweeds, contributing to their ability to scavenge free radicals and protect cells from oxidative damage. Phlorotannins have garnered significant attention due to their potential health benefits, including anti-inflammatory, anticancer, and antidiabetic properties (Perez-Vazquez et al. 2023). As potent antioxidants, they are crucial in maintaining cellular health and reducing the risk of chronic diseases. The presence of phlorotannins in seaweeds underscores their significance as valuable sources of natural antioxidants, with promising applications in pharmaceuticals, functional foods, and dietary supplements to promote human health and wellbeing (Gisbert et al. 2023).

4.3.2.2 Fucoidans

Seaweeds boast a rich repertoire of bioactive compounds, including fucoidans, renowned for their potent anti-inflammatory and anticancer activities (Rengasamy et al. 2020). These sulfated polysaccharides, prevalent in various species of seaweeds, possess remarkable biological properties that make them valuable in pharmaceutical and medical applications. Fucoidans exhibit anti-inflammatory effects by modulating immune responses and inhibiting inflammatory pathways, offering potential therapeutic benefits for arthritis and inflammatory bowel diseases. Additionally, their anticancer properties involve inducing apoptosis, inhibiting angiogenesis, and suppressing tumor cell proliferation, making them promising candidates for cancer prevention and treatment strategies. The multifaceted actions of fucoidans highlight their importance as natural compounds with significant health-promoting potential, positioning seaweeds as valuable resources for developing novel therapeutics and functional foods (Rengasamy et al. 2020).

4.3.2.3 Laminarins

Seaweeds are abundant sources of bioactive compounds, including laminarins, which exhibit notable immunomodulatory effects. Laminarins, a type of β-glucan polysaccharide found in various seaweed species, have garnered attention for their ability to regulate the immune system (Ha et al. 2024). These compounds can modulate immune responses by enhancing the activity of immune cells such as macrophages, natural killer cells, and dendritic cells. Laminarins stimulate the production of cytokines and other signaling molecules involved in immune regulation, promoting innate and adaptive immune functions. Their immunomodulatory properties have implications for health and disease, including potential applications in boosting immune function, combating infections, and managing immune-related disorders (Ha et al. 2024). The presence of laminarins in seaweeds underscores their significance as natural immunomodulators with promising therapeutic potential in immune health and disease management.

4.3.3 Seaweed-based biofuels

Seaweeds are increasingly being recognized as a sustainable and viable source for biofuel production. Their rapid growth rates and ability to thrive in marine environments without needing arable land or freshwater make them a highly eco-friendly alternative to traditional biofuel crops like corn or sugarcane. Unlike terrestrial biofuel sources, seaweeds do not compete with food crops for land and water resources, making them particularly valuable in addressing energy and food security challenges. Additionally, seaweeds can absorb carbon dioxide from the atmosphere, helping mitigate the effects of climate change by acting as a carbon sink (Nakhate and Van Der Meer 2021). Seaweed-based biofuels are primarily produced through anaerobic digestion, fermentation, and pyrolysis processes. These processes convert the carbohydrate-rich biomass of seaweeds, including species such as *Saccharina* and *Laminaria*, into biogas, bioethanol, and biodiesel. The bioethanol production process, for instance, exploits the high carbohydrate content (e.g., alginate, mannitol, and laminarin) present in certain seaweeds, making it a promising source of renewable energy (Kumar et al. 2022). Research is ongoing to improve these processes' efficiency and make seaweed biofuels commercially competitive with fossil fuels and other bioenergy sources. Commercial utilization of seaweed biofuels is still in its early stages, but several pilot projects and collaborations have been initiated worldwide. Countries like Japan, Norway, and South Korea are exploring large-scale seaweed farming for biofuel production, taking advantage of their extensive coastlines. In addition to direct energy production, seaweed biomass can be used in a circular economy model. The by-products of biofuel production, such as proteins and minerals, can be utilized as animal feed, fertilizers, or bioplastics, further enhancing the commercial viability of seaweed cultivation (Nakhate and Van Der Meer 2021; Kumar et al. 2022). As seaweed farming requires fewer inputs than land-based crops, it offers a low-cost, low-impact solution for sustainable biofuel production, with potential to scale up in the coming decades as technological advancements continue reducing costs.

5 Technological processes in high-value product production

The production of high-value products from seafood involves various technological processes, each contributing to the efficiency and quality of the final product.

5.1 Extraction and purification techniques

Efficient extraction and purification techniques are crucial for isolating high-value compounds from seafood resources.

5.1.1 Solvent extraction

Solvent extraction is a traditional method widely used for extracting oils and lipid-rich compounds from seafood, such as fish and shellfish. In this process, organic solvents like hexane or ethanol dissolve and extract lipids from the raw material (Caruso et al. 2020). The solvent extracts are then separated from the solid residue through filtration or centrifugation, followed by evaporation to recover the solvent and obtain the desired oil or lipid fraction (Caruso et al. 2020). Solvent extraction is known for its simplicity and effectiveness in obtaining oils from seafood, making it suitable for large-scale industrial applications. However, concerns about solvent residues and environmental impact have led to the development of alternative methods (Caruso et al. 2020).

5.1.2 Supercritical fluid extraction

Supercritical fluid extraction (SFE) is an advanced technique that utilizes supercritical fluids, typically carbon dioxide (CO_2), at specific temperature and pressure conditions to extract high-purity compounds from seafood (Wang et al. 2021). In SFE, CO_2 is pressurized above its critical point to become a supercritical fluid exhibiting both liquid and gas-like properties. This supercritical CO_2 is then used as a solvent to selectively extract target compounds, such as omega-3 fatty acids, without leaving behind solvent residues (Wang et al. 2021). SFE offers advantages such as high selectivity, low environmental impact, and the ability to produce extracts with high purity and quality. It is particularly suitable for extracting thermally sensitive compounds from delicate seafood matrices (Wang et al. 2021).

5.1.3 Enzymatic hydrolysis

Enzymatic hydrolysis involves using enzymes to break down complex biomolecules, such as proteins, into smaller peptides and hydrolysates with specific bioactivities (Cruz-Casas et al. 2021). In seafood, enzymatic hydrolysis is commonly used to produce protein hydrolysates from fish or shellfish proteins. Proteolytic enzymes, such as proteases, are added to the raw material to catalyze the hydrolysis of proteins into peptides of varying sizes. The resulting protein hydrolysates exhibit enhanced solubility, digestibility, and bioavailability compared to the original proteins (Cruz-Casas et al. 2021). Depending on the source material and enzyme used, they may possess bioactive properties, such as antioxidant, antimicrobial, or antihypertensive activities. Enzymatic hydrolysis offers precise control over the degree of hydrolysis and allows the production of tailored peptide mixtures with specific functional characteristics.

5.1.4 Membrane filtration

Membrane filtration techniques are used to separate and concentrate bioactive compounds from seafood extracts based on differences in molecular size, shape, and charge (Abhari and Mousavi Khaneghah 2021). Common membrane filtration methods include ultrafiltration, nanofiltration, and reverse osmosis. These techniques involve passing the seafood extract through a semipermeable membrane, which selectively allows certain molecules to pass through while retaining others (Abhari and Mousavi Khaneghah 2021). Ultrafiltration separates proteins and peptides from larger molecules and impurities based on their molecular weight. Nanofiltration and reverse osmosis further concentrate and purify the desired compounds by removing smaller molecules and ions. Membrane filtration offers advantages such as mild processing conditions, scalability, and the ability to retain the bioactivity of the target compounds. It is often combined with other extraction methods to achieve higher purity and concentration of bioactive compounds from seafood resources.

5.2 Fermentation and biotechnological applications

Fermentation processes harnessing the metabolic activities of microorganisms are instrumental in improving the bioavailability and functionality of seafood-derived products (Adegoke and Tahergorabi 2021). Through fermentation, beneficial microorganisms such as bacteria, yeasts, and molds transform raw seafood materials into value-added products with enhanced nutritional profiles, flavors, and textures. Further, fermentation can be employed to produce fermented fish sauces, fish pastes, and seafood-based condiments that not only improve the taste and aroma but also increase the digestibility and bioavailability of nutrients (Adegoke and Tahergorabi 2021). Moreover, fermentation can lead to the synthesis of bioactive compounds such as peptides, organic acids, and enzymes, which contribute to the health-promoting properties of fermented seafood products. In addition to fermentation, biotechnology plays a pivotal role in advancing seafood processing and production. Genetic engineering techniques are utilized to develop genetically modified organisms (GMOs) with enhanced traits, such as increased yield of desired compounds, improved resistance to pathogens, and enhanced nutritional content (Adegoke and Tahergorabi 2021).

5.3 Nanoencapsulation

Nanoencapsulation technology involves encapsulating bioactive compounds within nanoscale carriers to protect them from degradation, improve their stability, and enhance their delivery and absorption in the body. This technology offers numerous benefits for incorporating sensitive compounds, such as omega-3 fatty acids, into various food and pharmaceutical products. By encapsulating these compounds within nano-sized particles, nanoencapsulation shields them from environmental factors, such as oxygen, light, and moisture, which can cause degradation and loss of potency (Pateiro et al. 2021). Additionally, nanoencapsulation facilitates controlled release of the encapsulated compounds, ensuring optimal delivery to the target site in the body and maximizing their bioavailability. This technology enables the development of functional foods, dietary supplements, and pharmaceutical formulations with enhanced efficacy and consumer acceptability. Nanoencapsulation holds great promise for improving the stability and effectiveness of bioactive compounds, paving the way for the development of innovative products with enhanced health benefits and therapeutic potential.

5.4 Waste Reduction

Waste reduction is a key objective in sustainable seafood processing, as it directly impacts the industry's environmental footprint and enhances the efficient use of marine resources. Traditionally, 50-70% of fish biomass, including heads, bones, skin, and viscera, is considered waste during seafood processing. However, with technological advancements and innovative approaches, these by-products can now be converted into high-value products such as fish oils, proteins, and collagen, significantly reducing the waste generated (Nakhate and Van Der Meer 2021). For instance, FPH, produced by hydrolyzing fish by-products, has reduced processing waste by 40-60% and provided functional ingredients used in the food and nutraceutical industries (Pacheco-Aguilar et al. 2021).

6 Reducing environmental impact

In addition to reducing waste, sustainable seafood processing minimizes environmental impact by lowering greenhouse gas emissions and conserving water. By optimizing resource utilization and adopting energy-efficient technologies, seafood processing facilities have reduced their overall carbon footprint by up to 30%. Water consumption, often a major environmental concern, can be reduced by 20-50% through closed-loop systems that recycle and purify water used during processing (Shavandi et al. 2019). Processing plants worldwide increasingly adopt these systems to conserve resources and improve environmental sustainability.

7 Case Study – Iceland's circular economy model

A notable example of waste reduction in seafood processing is Iceland, where strict regulations mandate that almost 100% of the fish biomass be utilized. This practice has reduced waste while increasing the economic value derived from fish by-products. By converting fish waste into valuable products such as fishmeal, oils, and fertilizers, Iceland has established a circular economy model that minimizes environmental impact and maximizes resource use (Kumar et al. 2022).

8 Challenges and future directions

Unlocking the full potential of seafood resources requires addressing key challenges while advancing sustainable practices. Sustainable harvesting is critical, necessitating strategies like quotas, seasonal closures, and marine protected areas to prevent overfishing and promote species recovery. Collaborative efforts between governments, industry, and conservation groups are essential to harmonize sustainable fisheries management. Simultaneously, technological advancements can maximize resource utilization by optimizing extraction methods and reducing waste. Innovations like supercritical fluid extraction and membrane filtration can enhance the industry's capacity to derive high-value compounds while minimizing environmental impacts. Strong regulatory frameworks are needed to ensure product safety, quality control, and market transparency. Harmonized regulations across jurisdictions, informed by science and collaboration among stakeholders, can foster responsible seafood utilization. A coordinated, multidisciplinary approach will be vital for ensuring the seafood industry delivers nutritious and sustainable products for future generations.

Conclusion

The utilization of seafood resources to produce high-value products represents a promising pathway toward enhancing the sustainability and profitability of the seafood industry. Through the strategic application of advanced technologies and a steadfast commitment to sustainable practices, stakeholders in the seafood sector can unlock the full potential of marine resources, contributing to food security, economic prosperity, and environmental conservation. Adopting advanced technologies, such as nanoencapsulation, fermentation, and biotechnological approaches, offers opportunities to extract, purify, and enhance the bioavailability of valuable compounds from seafood. Nanoencapsulation, in particular, provides a means to protect sensitive bioactive compounds, such as omega-3 fatty acids, from degradation and enhance their delivery and absorption in the body, thereby enriching the functionality of food and pharmaceutical products. Furthermore, embracing sustainable practices is paramount to ensuring the long-term viability of seafood resources. Sustainable harvesting methods, informed by scientific research and guided by robust regulatory frameworks, are essential to prevent overfishing and mitigate environmental degradation. By prioritizing ecosystem health and biodiversity conservation, the seafood industry can safeguard marine ecosystems for future generations while maintaining a thriving seafood supply chain. Moreover, producing high-value products from seafood by-products and waste streams offers opportunities to minimize environmental pollution and promote circular economy principles. Through innovative approaches such as fermentation and enzymatic hydrolysis, valuable compounds can be extracted from seafood by-products, transforming waste into useful resources and reducing reliance on virgin raw materials. As the global demand for high-value seafood products escalates, the seafood industry faces challenges and opportunities. Technological advancements, regulatory frameworks, and collaborative initiatives will be crucial in navigating these complexities and realizing the full potential of seafood resources. By embracing innovation, fostering sustainable practices, and prioritizing environmental stewardship, the seafood industry can thrive in a rapidly evolving market landscape while contributing to the wellbeing of ecosystems and communities worldwide.

In summary, this review underscores the significance of using seafood resources for high-value products in the context of sustainability and economic development. By harnessing the potential of marine resources responsibly and innovatively, the seafood industry can play a pivotal role in addressing global challenges while creating opportunities for growth and prosperity.

References

Abhari, K., & Mousavi Khaneghah, A. (2020). Alternative extraction techniques to obtain, isolate and purify proteins and bioactive from aquaculture and by-products. *Advances in food and nutrition research*, *92*, 35–52. https://doi.org/10.1016/bs.afnr.2019.12.004.

Adegoke, S. C., & Tahergorabi, R. (2021). Utilization of seafood-processing by-products for the development of value-added food products. In R. Bhat (Ed.), *Valorization of agri-food wastes and by-products* (pp. 537-559). Academic Press. https://doi.org/10.1016/B978-0-12-824044-1.00012-X

Akram, S., Muzaffar, A., & Farooq, Q. (2023). Persistent organic pollutant fragile effects, their sources, transportation and state of the art technologies. *International Journal of Agriculture and Environment*, *2*(2), 26-45.

Ashraf, S. A., Adnan, M., Patel, M., Siddiqui, A. J., Sachidanandan, M., Snoussi, M., & Hadi, S. (2020). Fish-based bioactives as potent nutraceuticals: Exploring the therapeutic perspective of sustainable food from the sea. *Marine Drugs, 18*(5), 265.

Awuchi, C. G., Chukwu, C. N., Iyiola, A. O., Noreen, S., Morya, S., Adeleye, A. O., ... & Okpala, C. O. R. (2022). Bioactive compounds and therapeutics from fish: Revisiting their suitability in functional foods to enhance human wellbeing. *BioMed Research International*, *2022*(1), 3661866.

Azelee, N. I. W., Dahiya, D., Ayothiraman, S., Noor, N. M., Rasid, Z. I. A., et al. (2023). Sustainable valorization approaches on crustacean wastes for the extraction of chitin, bioactive compounds, and their applications: A review. *International Journal of Biological Macromolecules*, *253*(Pt 2), 126492. https://doi.org/10.1016/j.ijbiomac.2023.126492

Bhatt, P., Joshi, S., Bayram, G. M. U., Khati, P., & Simsek, H. (2023). Developments and application of chitosan-based adsorbents for wastewater treatments. *Environmental Research*, *226*, 115530.

Bruno, S. F., Ekorong, F. J. A. A., Karkal, S. S., Cathrine, M. S. B., & Kudre, T. G. (2019). Green and innovative techniques for recovery of valuable compounds from seafood by-products and discards: A review. *Trends in Food Science & Technology*, *85*, 10-22.

Burbridge, P., Hendrick, V., & Rosenthal, H. (2001). Social and economic policy issues relevant to marine aquaculture. *Journal of Applied Ichthyology*, *17*(4), 194-206.

Cadena, E., Kocak, O., Dewulf, J., Iñarra, B., Bald, C., et al. (2024). Valorization of seafood side-streams through the design of new holistic value chains: WaSeaBi Project. *Sustainability*, *16*(5), 1846.

Caruso, G., Floris, R., Serangeli, C., & Di Paola, L. (2020). Fishery wastes as a yet undiscovered treasure from the sea: Biomolecules sources, extraction methods and valorization. *Marine Drugs, 18*(12), 622.

Cooney, R., de Sousa, D. B., Fernández-Ríos, A., Mellett, S., Rowan, N., et al. (2023). A circular economy framework for seafood waste valorization to meet challenges and opportunities for intensive production and sustainability. *Journal of Cleaner Production, 392*, 136283.

Cruz-Casas, D. E., Aguilar, C. N., Ascacio-Valdés, J. A., Rodríguez-Herrera, R., Chávez-González, M. L., & Flores-Gallegos, A. C. (2021). Enzymatic hydrolysis and microbial fermentation: The most favorable biotechnological methods for the release of bioactive peptides. *Food Chemistry: Molecular Sciences, 3*, 100047.

D'Orazio, N., Gammone, M. A., Gemello, E., De Girolamo, M., Cusenza, S., & Riccioni, G. (2012). Marine bioactives: Pharmacological properties and potential applications against inflammatory diseases. *Marine Drugs, 10*(4), 812-833.

Dhandwal, A., Bashir, O., Malik, T., Salve, R. V., Dash, K. K., et al. (2024). Sustainable microalgal biomass as a potential functional food and its applications in food industry: A comprehensive review. *Environmental Science and Pollution Research, 1*-19. https://doi.org/10.1007/s11356-024-33431-6

Edo, G. I., Samuel, P. O., Nwachukwu, S. C., Ikpekoro, V. O., Promise, O., Oghenegueke, O., Ongulu, J., Otunuya, C. F., Rapheal, O. A., Ajokpaoghene, M. O., Okolie, M. C., & Ajakaye, R. S. (2024). A review on the biological and bioactive components of Cyperus esculentus L.: insight on food, health and nutrition. *Journal of the science of food and agriculture*, 10.1002/jsfa.13570. Advance online publication. https://doi.org/10.1002/jsfa.13570

Farmery, A. K., Alexander, K., Anderson, K., Blanchard, J. L., Carter, C. G., et al. (2022). Food for all: Designing sustainable and secure future seafood systems. *Reviews in Fish Biology and Fisheries, 32*(1), 101-121.

Fernandes, S. S., Coelho, M. S., & de las Mercedes Salas-Mellado, M. (2019). Bioactive compounds as ingredients of functional foods: Polyphenols, carotenoids, peptides from animal and plant sources. In M. R. S. Campos (Ed.), *Bioactive compounds* (pp. 129-142). Woodhead Publishing.

Gisbert, M., Franco, D., Sineiro, J., & Moreira, R. (2023). Antioxidant and antidiabetic properties of phlorotannins from *Ascophyllum nodosum* seaweed extracts. *Molecules, 28*(13), 4937.

Ha, H. A., Aloufi, A. S., & Parveen, B. (2024). Essential bioactive competence of laminarin (β-glucan)/laminaran extracted from *Padina tetrastromatica* and *Sargassum cinereum* biomass. *Environmental Research, 252*, 118836.

Haider, A., Khan, S., Iqbal, D. N., Shrahili, M., Haider, S., et al. (2024). Advances in chitosan-based drug delivery systems: A comprehensive review for therapeutic applications. *European Polymer Journal, 210*, 112983. https://doi.org/10.1016/j.eurpolymj.2024.112983.

Hamed, I., Özogul, F., & Regenstein, J. M. (2016). Industrial applications of crustacean by-products (chitin, chitosan, and chitooligosaccharides): A review. *Trends in Food Science & Technology, 48*, 40-50.

Islam, N., Hoque, M., & Taharat, S. F. (2023). Recent advances in extraction of chitin and chitosan. *World Journal of Microbiology and Biotechnology, 39*(1), 28.

Jiménez-González, C., Agrasar, A. M. T., Mallo, F., Rúa, M. L., & Fucinos, C. (2023). Red seaweed proteins: Valuable marine-origin compounds with encouraging applications. *Algal Research, 75*, 103262. https://doi.org/10.1016/j.algal.2023.103262

Kalasariya, H. S., Maya-Ramírez, C. E., Cotas, J., & Pereira, L. (2024). Cosmeceutical significance of seaweed: A focus on carbohydrates and peptides in skin applications. *Phycology, 4*(2), 276-313.

Kankariya, Y., & Chatterjee, B. (2023). Biomedical application of chitosan and chitosan derivatives: A comprehensive review. *Current Pharmaceutical Design, 29*(17), 1311-1325.

Khursheed, M., Ghelani, H., Jan, R. K., & Adrian, T. E. (2023). Anti-inflammatory effects of bioactive compounds from seaweeds, bryozoans, jellyfish, shellfish, and peanut worms. *Marine Drugs, 21*(10), 524.

Kumar, P., Yadav, N., Kumar, S., Bahadur, J., & Chauhan, P. K. (2022). Seaweed-based biofuels: Current status and prospects. *Bioresource Technology, 348*, 126618. https://doi.org/10.1016/j.biortech.2022.126618

Lomartire, S., & Gonçalves, A. M. (2023). Algal phycocolloids: Bioactivities and pharmaceutical applications. *Marine Drugs, 21*(7), 384.

López-Hortas, L., Flórez-Fernández, N., Torres, M. D., Ferreira-Anta, T., Casas, M. P., et al. (2021). Applying seaweed compounds in cosmetics, cosmeceuticals, and nutricosmetics. *Marine Drugs, 19*(10), 552.

Luo, J., Frank, D., & Arcot, J. (2024). Creating alternative seafood flavour from non-animal ingredients: A review of key flavour molecules relevant to seafood. *Food Chemistry, X*, 101400.

Magbanua, T. O., & Ragaza, J. A. (2024). Selected dietary plant-based proteins for growth and health response of Nile tilapia *Oreochromis niloticus*. *Aquaculture and Fisheries, 9*(1), 3-19.

Maneein, S., Milledge, J. J., Nielsen, B. V., & Harvey, P. J. (2018). A review of seaweed pre-treatment methods for enhanced biofuel production by anaerobic digestion or fermentation. *Fermentation, 4*(4), 100.

Martins, T. R., de Andrade, M. R., de Alcantara, M., Martins, I. B. A., Sant'Anna, L. J., et al. (2024). Exploring the consumer perception of seafood: A look at Brazilians. *International Journal of Gastronomy and Food Science, 36,* 100938.

Menon, V. V., & Lele, S. S. (2015). Nutraceuticals and bioactive compounds from seafood processing waste. In S. K. Kim (Eds.), *Springer handbook of marine biotechnology* (pp. 1405-1425). Springer Handbooks. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-53971-8_65

Milledge, J. J., Smith, B., Dyer, P. W., & Harvey, P. (2014). Macroalgae-derived biofuel: A review of methods of energy extraction from seaweed biomass. *Energies, 7*(11), 7194-7222.

Mohiuddin, A. (2019). Skin aging and modern age anti-aging strategies. *International Journal of Clinical Dermatology & Research, 7*, 209-240.

Mutalipassi, M., Esposito, R., Ruocco, N., Viel, T., Costantini, M., & Zupo, V. (2021). Bioactive compounds of nutraceutical value from fishery and aquaculture discards. *Foods, 10*(7), 1495.

Naghdi, S., Rezaei, M., Heidari, M. G., Tahergorabi, R., Lorenzo, J. M., & Mirzaei, F. (2024). Insights into fishery by-product application in aquatic feed and food: A review. *Aquaculture International,32,* 5851-5910. https://doi.org/10.1007/s10499-024-01447-x

Nakhate, P., & Van Der Meer, Y. (2021). A systematic review on seaweed functionality: A sustainable bio-based material. *Sustainability, 13*(11), 6174.

Ozogul, F., Cagalj, M., Šimat, V., Ozogul, Y., Tkaczewska, J., et al. (2021). Recent developments in valorization of bioactive ingredients in discard/seafood processing by-products. *Trends in Food Science & Technology, 116*, 559-582.

Pacheco-Aguilar, R., Gaxiola-Cortés, M. G., Velázquez-Gutiérrez, M. C., Hernández-Ledesma, B., & Montes-Montes, R. (2021). Seaweed bioactive compounds in animal and human health and food applications: Potential uses of seaweeds in sustainable food production systems. *Journal of Applied Phycology*, *33*(3), 1819–1832. https://doi.org/10.1007/s10811-020-02268-9

Pateiro, M., Gómez, B., Munekata, P. E., Barba, F. J., Putnik, P., Kovačević, D. B., & Lorenzo, J. M. (2021). Nanoencapsulation of promising bioactive compounds to improve their absorption, stability, functionality, and the appearance of the final food products. *Molecules, 26*(6), 1547.

Pereira, L. (2018). Seaweeds as a source of bioactive substances and skin care therapy: Cosmeceuticals, algotherapy, and thalassotherapy. *Cosmetics, 5*(4), 68.

Perez-Vazquez, A., Carpena, M., Barciela, P., Cassani, L., Simal-Gandara, J., & Prieto, M. A. (2023). Pressurized liquid extraction for the recovery of bioactive compounds from seaweeds for food industry application: A review. *Antioxidants, 12*(3), 612.

Power, A. M., Johnson, M. P., Marine, D. P., & Kelly, T. C. (2013). Seaweed as a resource for biofuels: An overview of technologies and challenges. *Marine Biotechnology*, *15*(4), 431-445. https://doi.org/10.1007/s10126-013-9502-7

Rengasamy, K. R., Mahomoodally, M. F., Aumeeruddy, M. Z., Zengin, G., Xiao, J., & Kim, D. H. (2020). Bioactive compounds in seaweeds: An overview of their biological properties and safety. *Food and Chemical Toxicology, 135*, 111013.

Román-Doval, R., Torres-Arellanes, S. P., Tenorio-Barajas, A. Y., Gómez-Sánchez, A., & Valencia-Lazcano, A. A. (2023). Chitosan: Properties and its application in agriculture in context of molecular weight. *Polymers, 15*(13), 2867.

Santos, H. O., Price, J. C., & Bueno, A. A. (2020). Beyond fish oil supplementation: The effects of alternative plant sources of omega-3 polyunsaturated fatty acids upon lipid indexes and cardiometabolic biomarkers: An overview. *Nutrients, 12*(10), 3159.

Shavandi, A., Hu, Z., Teh, S., Zhao, J., Carne, A., Bekhit, A. E.-D. A., & Bekhit, A. A. (2019). Seaweed polysaccharides as prebiotics, wound dressings, and drug delivery systems: A review. *Journal of Functional Foods*, 64, 103587. https://doi.org/10.1016/j.jff.2019.103587

Siahaan, E. A., Agusman, Pangestuti, R., Shin, K. H., & Kim, S. K. (2022). Potential cosmetic active ingredients derived from marine by-products. *Marine Drugs, 20*(12), 734.

Singh, S., Negi, T., Sagar, N. A., Kumar, Y., Tarafdar, A., et al. (2022). Sustainable processes for treatment and management of seafood solid waste. *Science of the Total Environment, 817*, 152951.

Stetkiewicz, S., Norman, R. A., Allison, E. H., Andrew, N. L., Ara, G., et al. (2022). Seafood in food security: A call for bridging the terrestrial-aquatic divide. *Frontiers in Sustainable Food Systems, 5*, 703152.

Sun, W., Shahrajabian, M. H., Petropoulos, S. A., & Shahrajabian, N. (2023). Developing sustainable agriculture systems in medicinal and aromatic plant production by using chitosan and chitin-based biostimulants. *Plants, 12*(13), 2469.

Tacon, A. G., Coelho, R. T., Levy, J., Machado, T. M., Neiva, C. R., & Lemos, D. (2024). Annotated bibliography of selected papers dealing with the health benefits and risks of fish and seafood consumption. *Reviews in Fisheries Science & Aquaculture*, *32*(2), 211-305.

Tas, A. A., & El, S. N. (2024). The food system with optimum nutrition vision. In A. A. Tas, & S. Nehir El (Eds.), *Smart Food Industry: The Blockchain for Sustainable Engineering* (pp. 3-24). CRC Press.

Välimaa, A. L., Mäkinen, S., Mattila, P., Marnila, P., Pihlanto, A., Mäki, M., & Hiidenhovi, J. (2019). Fish and fish side streams are valuable sources of high-value components. *Food Quality and Safety*, *3*(4), 209-226.

Venugopal, V. (2022). Green processing of seafood waste biomass towards blue economy. *Current Research in Environmental Sustainability*, *4*, 100164.

Veríssimo, N. V., Mussagy, C. U., Oshiro, A. A., Mendonça, C. M. N., de Carvalho Santos-Ebinuma, V., et al. (2021). From green to blue economy: Marine biorefineries for a sustainable ocean-based economy. *Green Chemistry*, *23*(23), 9377-9400.

Wang, Q., Wang, X., & Feng, Y. (2023). Chitosan hydrogel as tissue engineering scaffolds for vascular regeneration applications. *Gels*, *9*(5), 373.

Wang, W., Rao, L., Wu, X., Wang, Y., Zhao, L., & Liao, X. (2021). Supercritical carbon dioxide applications in food processing. *Food Engineering Reviews*, *13*, 570-591. https://doi.org/10.1007/s12393-020-09270-9

Xing, X., Han, Y., & Cheng, H. (2023). Biomedical applications of chitosan/silk fibroin composites: A review. *International Journal of Biological Macromolecules*, *240*, 124407. https://doi.org/10.1016/j.ijbiomac.2023.124407

Yang, L., Shu, T., Wang, K., Yuan, Z., & Zhang, X. (2023). Roles of marine shellfish proteins with high contents of angiotensin-converting enzyme (ACE)-binding peptides in nutrition support for hypertension. *Applied Sciences*, *13*(8), 4654.

Zhang, J., Ahmmed, M. K., Regenstein, J. M., & Wu, H. (2024). Recent advances of recycling proteins from seafood by-products: Industrial applications, challenges, and breakthroughs. *Trends in Food Science & Technology*, *149*, 104533. https://doi.org/10.1016/j.tifs.2024.104533