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VALORIZATION OF AGROINDUSTRY AND SEAFOOD WASTE TOWARDS BLUE ECONOMY: A WASTE TO WEALTH CONCEPT

Diverse uses of valuable seafood processing industry waste for sustainability: a review

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Abstract
Seafoods are rich in untapped bioactive compounds that have the potential to provide novel ingredients for the development of commercial functional foods and pharmaceuticals. Unfortunately, a large portion of waste or discards is generated in commercial processing setups (50–80%), which is wasted or underutilized. These by-products are a rich source of novel and valuable biomolecules, including bioactive peptides, collagen and gelatin, oligosaccharides, fatty acids, enzymes, calcium, water-soluble minerals, vitamins, carotenoids, chitin, chitosan and biopolymers. These fish components may be used in the food, cosmetic, pharmaceutical, environmental, biomedical and other industries. Furthermore, they provide a viable source for the production of biofuels. As a result, the current review emphasizes the importance of effective by-product and discard reduction techniques that can provide practical and profitable solutions. Recognizing this, many initiatives have been initiated to effectively use them and generate income for the long-term sustainability of the environment and economic framework of the processing industry. This comprehensive review summarizes the current state of the art in the sustainable valorisation of seafood by-products for human consumption. The review can generate a better understanding of the techniques for seafood waste valorisation to accelerate the sector while providing significant benefits.

Keywords Seafood waste · By-product · Valorisation · Waste to health · Gelatin · Ecology

Introduction

To meet the growing consumers demand, there is a need for a significant increase in global food production, which is well supported by marine products prepared from finfishes (anchoveta, pollock, tuna, herring, mackerel, whiting and carps), crustaceans (shrimp, krill, crab, lobster), molluscs (mussels, oysters, clams), cephalopods (squid and cuttlefish) and gastropods. In 2018, the global seafood production was 178.5 million metric tonnes (MT), with capture fisheries accounting for 96.4 MT of the total (FAO 2020). Depending on the operation, the solid waste produced by seafood processing facilities can range from 30 to 85% of the landed fish, with the exception of fish meal plants. The amount of the waste from shrimp or fish or squid rests on the intended use or demands of the consumers. The waste produced from fish shrimp processing may vary from 40 to 70% (Nirmal et al. 2020). Operations that process crab produce between 75 and 85% of the trash, while filleting plants produce between 30 and 60%. Meals are made from some of the aforementioned wastes. Because of their inherent nature, plants that produce fish meal generate very little waste. Investments in the capital, technology and fuel for a fish meal mill must be rather significant (Green and Mattick 1977).

Fish processing has a significant impact on environmental issues in general, particularly the issue of waste organic odour. Making fish sauce, protein concentrates and protein hydrolysates is one of the few initiatives taken to solve the issue of waste disposal. Gelatin has also been produced from the skin and bones and used as a food additive to improve the

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elastic qualities, consistency and stability of food products. Although gelatin from animals is preferable due to its higher dilution level and acetylation, the synthesis of gelatin from fish skin and bones also intends to exploit the accessory materials (Irwandi et al. 2009; Laufenberg et al. 2003). In addition to culinary items, they also make belts, briefcases, watch straps and handbags from fish skin. The production of fish crackers gains value from the utilization of fish bone debris in the form of hydroxyapatite since it helps to solve environmental issues. As a result of its chemical structure being similar to that of human bones and teeth, it can also be utilized as an implant material for hip extensions, heart valve replacements and other body implants, including bone replacement (bone substitution). Patients with osteoporosis and a high accident rate are increasingly using hydroxyapatite as a bone substitute material.

According to recent estimates, global fisheries discard more than 20 million metric tonnes of fish per year, or about 25% of the entire catch, including by-catch (or "non-target" species) and waste from fish processing (Caruso 2016; Guillen et al. 2018). Fish residues, which include whole waste fish, fish heads, viscera, skin, bones, blood, frame liver, gonads, guts, some muscle tissue, etc., are the source of numerous potentially valuable molecules, such as oils, proteins, pigments, bioactive peptides, amino acids, collagen, chitin and gelatin, for which a number of processes and technologies have been reported over the past few years (Jayathilakan et al. 2012; Maqsood et al. 2012). For proper implementation, there is considerable work to be done. In contrast to the exoskeletons of shrimp and other crustaceans, which are exceptionally durable and resistant to chemical or enzymatic destruction, organic fish wastes quickly degrade in hours or days, depending on the environmental circumstances. This implies considerable variations in how fish wastes and side streams are handled and valued along the treatment/valorisation chain, including how they are transported, stored and delivered to biorefining facilities. The largest EU research and innovation programme, Horizon 2020, has taken explicit measures to address this problem's root cause (BBI work plan 2018 2018).

There are concerns about the waste valorisation process, which involves turning waste materials into more usable goods, including fuels, materials and chemicals (Abdel-Shafy 1996). Long-term waste management has been a major focus of this strategy. However, the rapidly declining supply of fuel, natural resources and primary materials has pushed this idea back into the public eye and sparked new interest. More trash must be managed in a more sustainable and economical manner, as seen by the recent rise in waste production and landfilling worldwide. In order to meet industrial demands, many valorisation procedures are currently showing significant potential. Utilizing flow chemical technology to transform trash into useful goods is one of these potential waste valorisation solutions. According to Serrano-Ruiz et al. (2012), the benefits of continuous flow processes for biomass and food waste valorisation include ease of scaling up, effective reaction cycles that produce more yield, reaction control and a lack of need for catalyst separation.

Different kinds of fishery by-product waste

Fishery by-products can be categorized into two types.

Organic waste

The most prevalent components of the fishing business are organic by-products. These comprise the skin, viscera, red and white fish meat as well as a portion of the scales, bones and fins. These are all probable collagen sources (Pang et al. 2013). Fish collagen and its denatured by-product (gelatin) circumvent several religious prohibitions, slaughter requirements and safety concerns regarding the potential transmission of pathogens such as bovine spongiform encephalopathy and foot-and-mouth illnesses with the mammalian equivalents (Liu et al. 2015). These are the most prevalent structural proteins in both vertebrates and invertebrates, making up about 30% of all animal proteins (Loveday 2019).

Inorganic waste

Fish bones have long been regarded as a treasure trove of vitamins and minerals (Herpandi et al. 2011). Fish bone powder has been extracted from a variety of fish species, and its nutritional value has been established. Fish bone powder contains a lot of calcium (234 g/kg dry bone), mostly in the form of calcium carbonate and hydroxyapatite (HA) (Kang et al. 2006). There are two types of fish frames, or fish bones, available: cooked and uncooked. These fish frames frequently have attached meat. Uncooked bones can be obtained from the filleting industries, whereas cooked bones can only be obtained from dining establishments (which can be difficult to obtain) or after thermal processing, such as when tuna is treated prior to canning (Abdel-Moemin 2015). Including three samples of saithe, three samples of salmon and two samples of herring, Toppe et al. (2007) examined the chemical make-up, nutritional value and mineral levels of fish bones from eight different species. According to the findings, protein and ash levels were the primary determinants of the changes in lipid composition. The research also revealed minor variations in calcium and phosphorus levels as well as amino acid composition.

Challenges in reducing fish waste and progress towards "zero discards"

Many countries around the world are developing legislation to use sustainable technology to convert fish waste into resources with added value in order to comply with the Sustainable Development Goals (SDGs) of zero discards by 2030. Given the importance of prudent policies that strike a balance between top-down and bottom-up moves towards cultural attitudes and stakeholder acceptance, various nations are taking a variety of steps to prevent waste in the efficient utilization of fish waste materials. Among some of the notable initiatives are those of the FAO Committees on Fisheries (FAO 2014), the European Union's waste disposal prohibition (European Commission 2019) as well as the worldwide campaign towards food loss prevention and waste management (Save Food Initiative 2021).

Despite the fact that there are no strict benchmarking standards for recovering resources from fish by-products and by-catch, countries such as Austria, Switzerland, Germany, Argentina, Norway and the Netherlands have established a number of diverting targets outlining various ways to use fish waste. For instance, Argentina's "Zero Fish Waste Law" of 2005 established an 80% recycling and valorisation rate goal before 2018. The law forbids the land filling and incineration of fish waste, in addition to not exploiting its bioresources or energy. The National Fisheries Policy (NFP) framework 2020 offers a corporate strategy for administering the fishing industry through catch for pollutant prevention and resource reclamation, taking into account the international demand for Indian aquaculture products. The "Agricultural Export Policy 2018" and "Blue Growth Initiative" of the Indian government, as well as this NFP, include numerous crucial components for achieving the goals outlined in the SDGs. Modernizing the fish importance link to improve value-added goods, longer shelf lives and international trade rules is part of fishery governance (National Fisheries Policy 2020).

Traditional methods of utilizing seafood processing waste

Fish waste utilization via fish salting, smoke-drying, sun-drying and solvent extraction are some of the primary processes used to value fish waste because of their economic benefits (Coppola et al. 2021). Developing nations use solar dryers to produce better-quality dehydrated fish products. Fish oil may be extracted using a hydrophobic solvent, fish meal can be produced through wet pressing and biofuel can be produced through esterification and esterification from fish waste (Muzaddadi et al. 2016). A new FAO technical evaluation claims that fish by-products account for nearly 35% of the fishmeal and fish oil consumed in poor countries today (FAO 2021).

Developed nations like Japan, France and Southeast Asia regularly utilize enzyme technology to generate these compounds on a big scale, even if the use of fishery waste for fish protein hydrolysates is restricted in several nations due to expense considerations (Ghaly et al. 2013). The fish allowance convoy techniques are being reinforced in Barbados and Saint Kitts and Nevis to produce items that will satisfy potential demand (Ordóñez-Del Pazo et al. 2014). Similar to Bangladesh, fish silage processing in Thailand was improved by the use of chemical acidification technology to increase productivity (Food and Organization 2018). Despite the enormous improvement that assembling nations have made in using fish by-products, many nations exhibit a scarcity of earnings in refining them to extract useful ingredients due to financial constraints and technology gaps (Villamil et al. 2017). Overall, the majority of traditional methods for using fishery wastes are inefficient with regard to energy and resources, in addition to requiring the use of a number of chemicals. By utilizing technical advancements to fill in the gaps in the already accessible knowledge on fish waste valorisation, it will take some time to develop ways to use fish by-products efficiently in the manufacture of economically significant value-added products.

Conventional methods of valorising fish waste and the need for new technology

Utilized fish waste side streams are turned into a sizeable amount of animal and aquaculture feed. Common unit processes include wet pressing, smoking, enzymatic hydrolysis, fermentation, solvent-solid liquid extraction, steam distillation and other techniques (Aspevik et al. 2017). Steaming through cooking is a common first step in an industrial valorisation process to prevent enzymatic and microbiological deterioration and enable the release of water and oil (Fig. 1). Subsequently, centrifugation, solid cake as well as press liqueur are the by-products that are left over. The aqueous, oil and solid phases of liquid parts of decanted fishery waste materials can be further separated by heating at a temperature of around 95°C (Ghaly et al. 2013). To prevent microbial growth, fish waste is heated and air-dried to produce flour that has a moisture level of 10% or less. Compounds that are volatile and semi-volatile at room temperature may degrade during this process (Ferraro et al. 2013).

Fish by-products are a valuable source of proteins, lipids and other micronutrients for the pharmaceutical, biomedical and cosmetic sectors. In fish waste biomass, resources are

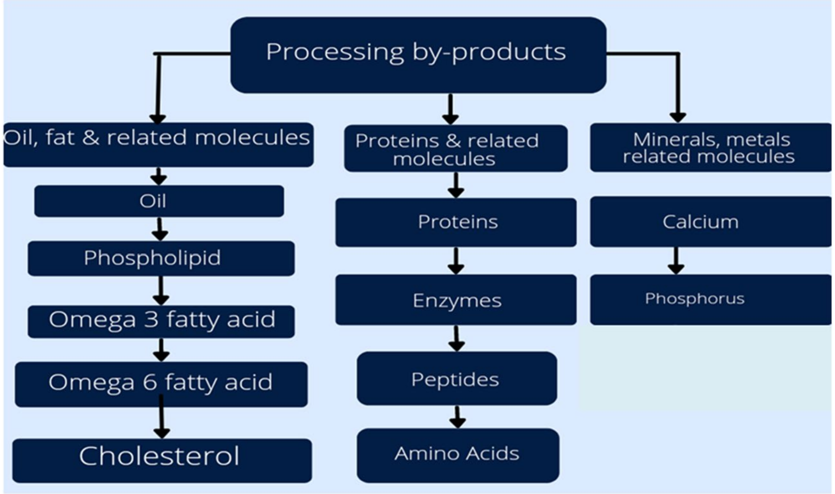

Fig. 1 Utilization of fish processing by-products through different valorisation methods

heterogeneously distributed and necessitate precise management of bioconversion processes. In addition to being rich in endogenous enzymes, they are also highly perishable and contain a high microbial burden (Younes and Rinaudo 2015). Due to enzymatic lysis of succulent fish muscle, autolytic damage, oxidation, microbial spoilage and other factors, the organic part decomposes rapidly in hours (Caruso et al. 2020). The fish meal processing techniques frequently use temperatures exceeding 150°C to reach a comfortable moisture percentage as well as inactivate enzymes, degrading precious heat-sensitive chemicals in the process. The standard valorisation method can readily cause the increased fat and protein percentages of the fish by-products to oxidise. The fishery waste material ability to be accepted is substantially hampered by the accumulation of off tastes brought on by oxidative damage (Alfio et al. 2021). Through the enzymatic hydrolysis process, fish protein hydrolysates are created, and they are sieved to remove any bones (Abraha et al. 2017). Similar to this, fish waste–based bioactive peptides are created by hydrolyzing waste biomass proteins and then fragmenting those (Vázquez et al. 2020). It is possible to produce biomethane through anaerobic digestion and co-digestion of vegetable and fish by-product streams (Kébé et al. 2021). Fish can be preserved by smoking and drying using the biogas that is produced. Their consequences on nutritive importance, safety as well as general sensory acceptability are limitations, nevertheless. The use of “high-value” biomaterials is still debatable when hydrothermal carbonization is used to create hydrochar from watery fish waste material biomass (Kannan et al. 2017).

The reasonable method for valuing fish waste would be to include the nutritive fractions of nutrient-dense fish waste by-products in the everyday diet; however, nutrient bioabsorption is a major obstacle. Due to this, it is essential to extract, refine as well as concentrate the beneficial chemicals in order to boost both their bioavailability and bioactivities. It is clear that a cell disruption procedure is necessary to optimise the output of bioactive chemicals because combinations of interest are primarily found inside cellular organelles in fish tissues (Nemati et al. 2016). Following deproteinization, demineralization and deacetylation procedures, the polymers chitin and chitosan can be extracted via fishery waste material to produce another significant commercial commodity (Younes and Rinaudo 2015).

Gelatin and collagen derived from seafood by-products

The skin and bones of fish contain rich sources of both collagen and gelatin, which are employed in the culinary, cosmetics as well as the pharmaceutical industry. Unlike collagen and gelatin from bovine sources, collagen and gelatin from fish skin have no danger of mad cow infection or bovine spongiform encephalopathy. A special sequence of amino acids called glycine-proline-alanine gives gelatin its antioxidative properties (Byun et al. 2005; Kim and Mendis 2006). Researchers are becoming more interested in modifying mammalian collagen to use in food and pharmaceutical items, and they are also interested in the collagen and gelatin recovered from fish (Karim and Bhat 2009).

Chitin and Chitosan from seafood waste products

Except for the shells of shrimp, crab and squid, chitin is a structural element of fish scales (Ferraro et al. 2010). Marine chitins have been used to make a wide range of bioactive chemicals, comprising chitinase, chitosanase, chitooligomers, antidiabetic and antioxidants substances as well as prodigiosin, a potential cancer treatment candidate (Nguyen et al. 2019; Wang et al. 2020a). Chitin is the principal source of chitosan in commercial production, and it is deacetylated by adding alkali solutions during the process. Chitin and chitosan are common marine polysaccharides, and due to their unique biological and physicochemical properties, they possess drawn a plenty of revenue in nutrition, pharmaceutical and fitness applications throughout the years (Ferraro et al. 2010). For biomedical and pharmaceutical uses, as well as in the food sector for food additives and packaging materials, chitin and chitosan's adhesive nature is a very important trait. They also have antibacterial and antioxidant capabilities (Jayakumar et al. 2011). Environmentally friendly methods for extracting and purifying chondroitin sulphate, chitin/chitosan as well as hyaluronic acid via seafood by-products were reviewed (Vázquez et al. 2013). These methods include numerous enzymatic, microbial, chemical and membrane technologies.

Nitrogenous compound/concentrated fish protein

The nitrogenous fraction consists of a broad spectrum of proteins, peptides, amino acids and their by-products. Novel and affordable methods must be developed to recover nutritious proteins from untapped sources due to the global shortage of these proteins (Henchion et al. 2017). Proteins can be recovered while keeping the majority of their natural qualities from seafood processing waste, which has a maximum protein content of roughly 60%. Protein can now be recovered from waste materials using bioconversion techniques. These use biophysical modifications to cause their coagulation and macromolecule precipitation. The discussion of these follows.

Fish protein hydrolysate

The by-catch or underutilized fish can be used effectively with the help of fish protein hydrolysate (FPH) technology. Due to their small size, appearance, taste and flavour, these fish have poor consumer preference and acceptability, which results in low commercial value. Through the use of appropriate and established operational methods, FPH could assist in reducing these waste by-products. The final product's physical, chemical and organoleptic qualities can be enhanced by the enzymatic processing of numerous biopolymers found in food, including pectin, proteins as well as polysaccharides. For easy acceptance in the food industry and for a broad spectrum of requisitions in various food enterprises, including milk substitutes, flavour enhancers in confectionery products, beverage stabilisers, protein supplements, animal food and microbial media, the nutritional qualities of protein are not degraded during the enzymatic extraction process under controlled pH conditions (Lotfian et al. 2019). The majority of these diets are made up of peptides and are a sufficient source of amino acids. FPH is gaining popularity because it may have a variety of bioactive qualities, such as antioxidant, antibacterial, immune-modulating, neuroactive, antihypertensive and mineral or hormone-regulating abilities (Chaklader et al. 2020; Logarušić et al. 2020; Gao et al. 2021).

The fish protein hydrolysates can be made from the proteins extracted through seafood processing waste using proteolytic enzymes from either a variety of sources, comprising vegetation, animals as well as microbes (Nag et al. 2022). Examples of these enzymes include Alcalase, Flavourzyme as well as Protamex (FPHs). The optimal incubation parameters are 50–70°C, a substrate-to-enzymatic proportion of 1–50 as well as an incubation time of approximately 2–4 h. The amount of hydrolyzed influences the dispersion, water-holding capacity, emulsification and foam-forming characteristics of the hydrolysate, as well as the quantity and chemical composition of the peptides generated. Ultrafiltration and vacuum evaporation are two methods for concentrating the FPH. They often have a positive impact on feeding efficiency and growth performance at modest inclusion levels (Chalamaiah et al. 2012; Vijaykrishnaraj and Prabhasankar 2015). Commercial proteases were applied to fish frames without heads from Atlantic cod as well as salmon for 2 h. Alcalase-treated salmon and pepsin-treated cod both produced 64% and 68% proteins, respectively (Liaset et al. 2003). Alcalase and pancreatin were used in an enzymatic process to extract proteins, chitin and astaxanthin from shrimp. When compared to pancreatin, Alcalase was more effective, increasing recovery of proteins from 57.5 to 64.6% and that of astaxanthin from 4.7 to 5.7 mg per 100 g of dry waste, at a degree of hydrolysis of 12%. From 26% to 28% of the protein was recovered when the DH was raised from 6 to 12% (Routray et al. 2019). Sixty-five percent of the protein was recovered using Alcalase hydrolysis of the industrial waste material from *Xiphopenaeus kroyeri* shrimp (Holanda and Netto 2006).

Fish protein isolates

The most popular approach, due to its affordability, for obtaining seafood protein isolates is via isoelectric solubilization/precipitation (or pH shift). The method comprises three phases: in the initial phase, the pH will be either raised or lowered to solubilize the muscle proteins; in the second phase, separates will be used to eliminate skeletons, scales, neutral lipids as well as broken cell membranes. Protein precipitate at its isoelectric point is a component of the last stage (pH 5.2–6). Increased protein recovery percentages alongside prompted the improvement qualities of the recoverable proteins, including such emulsifier, gelling, solubility and water-holding capacity, alongside foaming as well as oil-holding capacity, which are among the most frequently mentioned advantages of this technology (Sasidharan and Venugopal 2020; Tang et al. 2021).

Protein isolates from various marine raw materials for the production have been obtained using the pH-shift method in numerous investigations, and the recovered proteins have been put to use in a variety of applications. For instance, in a recent work (Surasani et al. 2020), protein isolates were produced using pangas fish processing waste via solubilization at pH 13.0 and precipitating at pH 5.5 and added to pangasius mince sausage. The researchers noted that the incorporation of these protein isolates at a level of 10 g/100 g resulted in sausage having enhanced functioning without significantly changing overall sensory attributes of the sausage. In a variety of studies, ponyfish, *Equulites klunzingeri*, discarded types of fish, were utilized to extract fish protein isolates using the pH-altering technique. The isolates that were generated by this research were then utilized as a protective layer in the microencapsulation of anchovy oils (*Engraulis encrasicolus*) (Ozogul et al. 2021).

Omega-3 polyunsaturated fatty acids: fish oil production

Marine organisms like fish, seafood and algae are the most major naturally occurring sources of omega-3 polyunsaturated fatty acids (PUFAs). Marine phytoplankton is the primary source of PUFAs in the trophic chain and is the primary source of nourishment for these marine organisms. Fish is the most common source of omega-3 PUFAs in the average person's diet, and the Scombridae and Clupeidae families' blue oily fish have the highest levels of omega-3 (Mataix-Verdú 2009). It is important to keep in mind, nevertheless, that some fish species may have high concentrations of hazardous compounds like methylmercury, polychlorinated biphenyls (PCBs), dioxins, heavy metals and other environmental pollutants. The health advantages of omega-3 intake may be jeopardised if contaminated fish is regularly ingested (Kris-Etherton et al. 2002). This viewpoint suggests that small oily fish with brief life cycles are preferable as a source of omega-3 PUFAs since the bioaccumulation of pollutants is reduced (Canli and Atli 2003). Numerous physiological processes, including the maintenance of cell membrane fluidity, signalling and cell-to-cell communication, are carried out by these PUFAs, which are stored in membrane phospholipids (Gammone et al. 2019). Inflammation can be reduced by *n*-3 PUFAs, which may also assist in minimising the chance of developing chronic illnesses like cancer, arthritis and heart disease. They also control the neurological system, blood pressure, haematological coagulation, glucose tolerance and other processes (Wall et al. 2010).

Antimicrobial peptides isolated from fish waste

There have also been reports of conventional and non-conventional antimicrobials in fish (Smith et al. 2010; Smith and Fernandes 2009). The pardaxins, which were identified from the skin glands of Red Sea Moses sole, *Pardachirus marmoratus*, were the first family of peptides with these characteristics to be found in fish. They have action against both Gram-positive and Gram-negative bacteria with pore-forming capabilities. The family of piscidins, which includes pleurocidins and piscidins, comprises a family of linear, amphipathic AMPs. The first 25-residue peptides that were initially isolated in the skin mucus of the winter flounder, *Pleuronectes americanus*, have a wide range of antimicrobial actions, including the ability to block DNA, RNA and protein synthesis. The second type of peptide is a 22-residue one that was initially isolated from the skin and gills of a hybrid striped bass (*Menticirrhus saxatilis* × *Morone chrysops*) and is also present in other Perciformes. The red sea bream *Chrysophrys major*, dicentracin from the European bass *Dicentrarchus labrax*, chrysophsins from the red sea bream and epinecidin from the orange-spotted grouper *Epinephelus coioides* all belong to the piscidin family.

Amino acid sequence of peptides

An amino acid sequence that is produced from dietary proteins may have physiological effects. Himaya et al. (2012) used Q-TOF-ESI mass spectroscopy to analyse isolated peptides from Pacific cod skin gelatin hydrolysate. A pure peptide's bioactivity is significantly influenced by the composition of its amino acids. Zhang et al. (2012) discovered that hydrophobic amino acids with non-polar aliphatic groups, such as Val, Trp, Tyr, Leu, Ile, His and Pro, react with non-polar PUFAs and have a considerable impact on radical scavenging in heavy lipid–containing meals. When radical scavengers (Phe, Trp and Tyr) give protons to electron-deficient radicals, stable reactive oxygen species (ROS) are created (Sarmadi and Ismail 2010). Gly, Pro and Leu amino acids increase the ACE inhibitory action (Mendis et al. 2005). According to the study conducted by Cushman and Cheung (1971), tryptophan, tyrosine, proline and phenylalanine were found to be suitable C-terminal amino acids for a peptide binding to ACE as a competitive inhibitor. The majority of the identified ACE peptides are typically short peptides with a proline residue at the C-terminal end. Proline is known to inhibit the digestion of enzymes and can enter the bloodstream from capillaries in the form of short peptides (Korhonen and Pihlanto 2006; Pan et al. 2005). Additionally, the C-terminal positions Pro, Phe and Tyr as well as the N-terminal positions Val and Ile have all demonstrated strong ACE inhibitory action.

Squalene

From the overall lipids produced by the thraustochytrid *Aurantiochytrium* sp. T66, squalene, a useful nutraceutical and medicinal substance, was efficiently isolated. This strain is a good fit for the idea of a sustainable biorefinery due to its multiproduct paradigm. Squalene is a polyunsaturated triterpenoid that serves as a precursor to many bioactive substances, including bile acid, cholesterol, hopanoids and steroids, in both plants and animals (Gohil et al. 2019). It can be broken down into smaller alkanes due to its branching hydrocarbon nature (Oya et al. 2015). Squalene is typically extracted from the liver oil of whales and deep sea sharks, but this source has a number of drawbacks, including the presence of pollutants, a foul smell, an unpleasant taste and an adverse effect on aquatic ecosystems (Pollier et al. 2019). Additionally, contamination with chemically similar substances like cholesterol makes it difficult to extract squalene from liver oils later. Squalene reduces serum cholesterol levels, enhances immunological function and inhibits the growth of tumours (Brown et al. 2019; Garcia-Bermudez et al. 2019). It is employed as an antioxidant in the cosmetics sector to snuff out molecular oxygen (O_2) (Güneş 2013). Squalene can be produced by various plants, but this is insufficient for industrial use (Popa et al. 2015), making the sustainable manufacture of squalene from thraustochytrids the only viable option.

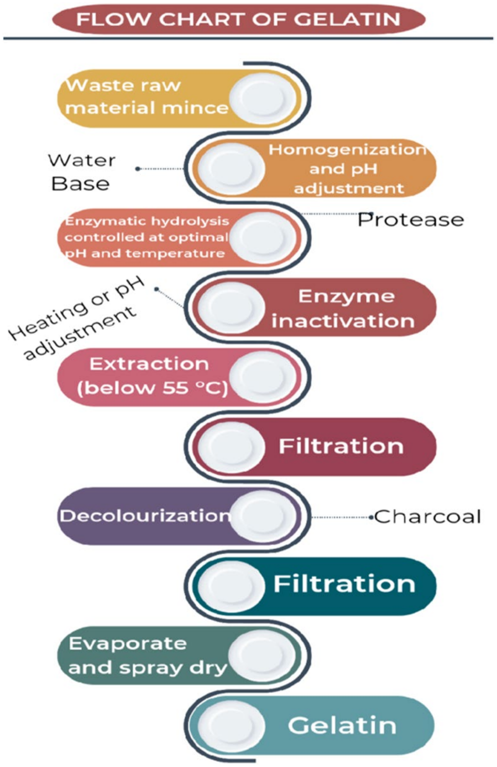

Fig. 2 Flow chart of gelatin preparation through fish by-products (Sultana et al. 2018)

Calcium phosphates from fish waste bones

Both naturally occurring organic and inorganic source materials can be used to make calcium phosphates. According to Terzioğlu et al. (2018), fish bones are one of the biological or organic sources that might be used to create calcium phosphates (Fig. 2). Essential seafood for humans is oyster, one of the most commercially cultivated shellfish in the world (Wang et al. 2022). Many shells are produced throughout the oyster processing process. Calcium, one of the essential nutrients for human health, may be found in abundance in oyster shells. Calcium is crucial for human life processes such as bone development, muscle contraction and cell phagocytosis (Bass and Chan 2006). The development of calcium supplements has attracted interest because the majority of individuals cannot obtain adequate calcium through diet alone (Cho et al. 2004). Currently, an ionic calcium supplement leads the market, but it is difficult to absorb since it precipitates in the digestive system, resulting in a low bioavailability (Vavrusova and Skibsted 2014). It is crucial to boost the bioavailability of calcium by resolving digestive system issues in order to decrease the incidence of calcium insufficiency in individuals.

High biological activity, a high rate of absorption and minimal side effects are all benefits of amino acid–chelated calcium (Wang et al. 2020b). However, it is highly expensive to produce calcium via chelated amino acids, and it may also result in undesired colour changes and fat oxidation. Peptide-calcium chelate has a lot of interest right now (Tian et al. 2021). It is relatively stable because phytic acid, oxalic acid and other acids prevent calcium precipitation. Additionally, it can stop the hydrolysis of peptides by inhibiting the peptidase's hydrolysis activity on the brush edge of the intestinal tract. The tiny peptide transportation channel, on the other hand, allows chelated calcium to be absorbed without being competitively inhibited by other metal ions (Gloux et al. 2019). Numerous research studies have described the creation of peptide-calcium chelates using commercial calcium (calcium chloride) and peptides from various protein sources, such as bovine serum protein (Choi et al. 2012) and whey protein (Cai et al. 2015).

Biorefinery approach for valorisation of seafood discards

The seafood industry produces a substantial amount of waste. They comprise low-value underutilized fish obtained as by-catch in commercial fishery activities, which are also processed discards made up of shell, skull, bones, gut, fins and skin, and large amounts of wastewater generated as effluents. The by-catch, effluents and discards are abundant in minerals, protein, amino acids, fats with healthy amounts of polyunsaturated fatty acids, carotenoids as well as other nutrients. Therefore, the loss of nutrients and significant environmental risks are brought on by the seafood discard (Venugopal 2021). The term "biorefinery" refers to a paradigm shift away from the utilization of fossil fuels (oil) in the chemical industry and towards the use of biologically based, renewable sources (biomass). Fuels, energy and chemicals are the primary outputs of oil refineries; therefore, developing an industrial counterpart that produces the same outputs (energy, fuels and chemicals) from biomass processing is necessary to replace oil (Cherubini 2010). Biomasses include intended crops, wastes or novel biomasses fed on reclaimed land or ponds (algae). The global growth of the bio-based chemical industry is threatened by the utilization of waste in the "food vs. fuel" debate (Ajanovic 2011).

Waste generated during the processing of fish can be a viable reusable biomass for biorefineries. The biorefinery strategy envisions turning fish waste into goods with additional value, such as biofuels, chemicals for industry, animal feed, organic fertiliser, nutraceuticals and others. Some of the key characteristics of the process include low cost and simplicity of operation through labour, energy and material cost reductions while retaining high output (Sahu et al. 2016). The shell refinery process, for instance, sequentially treats waste from crab shells to recover chitin, proteins, lipids, carotenoids, calcium carbonate and chitin monomers (Hülsey 2018). In order to extract gelatin, lipids, fish protein hydrolysate containing bioactive peptides and fish peptones from the heads, skin and bones of fish discards, Vázquez et al. (2019) combined Alcalase hydrolysis with bacterial fermentation. According to Cahú et al. (2012), an integrated method for recovering chitin and chitosan, protein hydrolysate and sulphated and amino polysaccharides from shrimp heads uses autolysis. Astaxanthin, hydrolyzed protein and chitin can be extracted sequentially or simultaneously from crustacean shell waste using lactic acid fermentation and green extraction techniques such as filtration and centrifugation (Vázquez et al. 2017; Routray et al. 2019). Similar results were obtained when fish waste was fermented anaerobically; the main by-products were methane and liquid fertiliser. The purchase price of methane is a crucial factor influencing the economics of the biorefinery (Ratky and Zamazal 2020). An additional biorefinery concentrates *n*-3 PUFA while also extracting oil from fish waste and transesterifying it with ethanol. Other products of the refinery include fishmeal, glycerol and liquid biofuels made of saturated and short-chain unsaturated fatty acids. The method drastically reduces CO_2 emissions and supplies thermal energy (Fiori et al. 2017).

A biorefinery developed within an EU-funded project combines chitin demineralization by *Serratia* spp. and *Lactobacillus* spp. and enzymatic degradation of chitin by chitin-degrading enzymes from *Serratia marcescens*, *Amantichitinus ursilacus* and *Andreprevotia ripae*. The produced *N*-acetylglucosamine monomers may be used to create new bio-based polymers. It is possible to feed the generation of biogas with proteins and lipids (Sieber et al. 2018). With a daily effluent discharge of at least 1300 m^3, Eurofish processes about 200 tonnes of tuna. The business combined seafood waste-to-energy technologies, producing 1300 m^3 of methane every day. Energy use was cut by 35–40%, while costs associated with wastewater treatment were cut by 50%. Since the facility began operating in March 2016, it has provided evidence of the viability of biorefineries based on the valorisation of seafood waste (Fluence 2019).

Fish waste/by-product utilization

Minerals, proteins and lipids are plentiful sources of fishery waste materials (Table 1). Through using end-up waste fish scraps from five marine organisms (white croaker, horse mackerel, flying fish, chub mackerel as well as sardine), Khan et al. (2003) explored the potential for producing fish protein hydrolysate through enzymatic treatment. Their findings suggested that fish protein hydrolysate could be utilized as a cryoprotectant to prevent the conformational changes of lizard fish surimi protein molecules throughout the frozen storage. According to Ohba et al. (2003), enzymatic hydrolysis can produce valuable chemicals from collagen or keratin found in fish and cattle waste, creating new nutritionally beneficial dietary components. Protein hydrolysates and peptides were made using collagen fibrils that contained wastes

Table 1 Composition of fishery waste material on a dry matter basis

S. no.	Parameters	Fish discards
1	Crude protein (%)	57.92 ± 5.26
2	Ash (%)	21.79 ± 3.52
3	Fat (%)	19.10 ± 6.06
4	Crude fibre (%)	1.19 ± 1.21
5	Calcium (%)	5.80 ± 1.35
6	Phosphorous (%)	2.04 ± 0.64
7	Potassium (%)	0.68 ± 0.11
8	Sodium (%)	0.61 ± 0.08
9	Magnesium (%)	0.17 ± 0.04
10	Iron (mg/kg)	100.00 ± 42.00
11	Zinc (mg/kg)	62.00 ± 12.00
12	Manganese (mg/kg)	6.00 ± 7.00
13	Copper (mg/kg)	1.00 ± 1.00

Adapted from Ghaly et al. (2013)

from pig skin as well as yellow tail fish bones. The utilization of these fish protein hydrolysates as dietary additives is conceivable (Morimura et al. 2002). For the manufacturing of fish silage, fish feed as well as fish sauce, enzymatic and bioactive peptides are derived via fishery waste or by-catch waste materials (Gildberg 2004). Vázquez et al. (2004) claim that discarded fish entrails undergo autohydrolysis to yield peptone hydrolysates, which are then used in a microbiological medium to stimulate the development as well as the generation of bacteriocin through lactic acid bacteria. Fish processing waste materials can be put to use in a variety of other ways, including the creation of fishmeal, the incorporation of fish as well as protein concentrates as a source of food, the utilization of fish minced, the use of fish gelatin

Table 2 Fishery by-product utilization and applications

Sl. no.	Products	Source	Application/example	Reference
1	Fish organ probiotics	Teleost fish waste	*Enterobacter* sp.; *Aeromonas* spp.	Merrifield and Rodiles (2015)
2	Fishmeal and fish oil	Marine by-products	60% of fishmeal and 80% of fish oil	Péron et al. (2010)
3	Nutraceuticals	Fishery discards	Natural food additives, bioactive compounds	Venugopal and Lele (2015)
4	Fish protein hydrolysis	Marine waste tuna, mackerel, yellowfin sole and Alaska pollock	Anti-inflammatory and antioxidant activities	Je et al. (2005, 2007); Park et al. (2004)
5	Enzymes extracted	Fishery by-catch or by-products	Seafood processing and production of FPH	Menon (2016)
6	Biodiesel	Fish by-products	Biodegradable and renewable energy source	Samat et al. (2018)
7	Biorefinery	Fishery by-catch and processing by-product management	Oil refineries are fuels, energy and chemicals	Kerton et al. (2013)
8	Bioactive peptides	Fish muscle waste	Immune modulatory and antioxidative properties	Choi et al. (2000)
9	Antimicrobial peptides	Fishery waste materials	Gram-positive and Gram-negative bacteria with pore-forming activities	Smith et al. (2010); Smith and Fernandes (2009)
10	Collagen and gelatin	Fishery by-products	Cosmetic and regenerative medicine antioxidant properties	Karim and Bhat (2009); Kim and Mendis (2006)

Table 3 Biological activities and industrial applications of fish waste–based valuable compounds

Types of waste	Specific waste	Bioactive compound	Industrial application	Reference
Shrimp	Shrimp waste	Cholesterol	Supplement of nutrients in fish production	Lopez-Cervantes et al. (2006)
Marine protist *Aurantiochytrium* sp.	Food waste hydrolysates	Squalene	Pharmaceutical industry	Patel et al. (2020)
Sardine (*Sardina pilchardus*)	Viscera	Lipids and phospholipids	Antibacterial, antiviral and antitumoural	Dumay et al. (2006)
Fish waste	By-product from fish processing plant	Bio-oils	Efficient utilization in industry	Norziah et al. (2009)
Fish processing industry	Fish processing waste	Proteins, amino acids, omega-3 fatty acids	Animal feed, pharmaceuticals and medicinal properties	Ghaly et al. (2013)
Fish processing by-products	Fish bones	Calcium phosphates	Biomedical application and hydroxyapatite ceramics	Terzioğlu et al. (2018)
Sharks	Viscera, head, skin, scales, bones, etc.	Shark cartilage	Health products; stimulate the rapid growth	Suresh et al. (2018)
Seafood processing industry waste	Fish waste	Omega-3 fatty acids	Application in biorefinery strategies for the valorisation	Melgosa et al. (2021)
Fish processing waste	Head, skin, trimmings, fins, frames, viscera and roe	Purified peptide	Antihypertensive, antioxidative and anticancer activities	Ishak and Sarbon (2018)

and the utilization of fish as a source of nutritional and health components (Tables 2 and 3).

Valorisation of crab by-products/processing waste

The liver (or hepatopancreas or brown flesh) as well as shells, which account for more than 50% of the crab's weight, are indeed the wastes and discards that manufacturers are most interested in (Malaweera and Wijesundara 2013). For both the production of various crab- and non-crab-based processed foods (bases, stocks and soups), brown flesh is employed as just a source of seasoning (Goldhor and Regenstein 2007). Exoskeletons of crabs are abundant sources of structurally diversified bioactive nitrogen-containing substances, including proteins, minerals (mostly carbonates of both calcium and magnesium), colours, flavourings as well as chitin (Selva 2020; Venugopal and Gopakumar 2017; Xu et al. 2019). Even the cooking waste products from crab processing facilities, which are frequently thrown away as waste, are concentrated via reverse osmosis and turned into solid material, primarily proteins, minerals and flavourings. In the food processing industry, the granular constituents (retentates) could be employed to generate new products and also as natural smells (Tremblay et al. 2020). Alongside expanded attempts to enhance crabs' output, additional garbage is already produced by the crab processing sector, leading to issues concerning waste management and environmental implications. To counteract the slow decomposition of organic and its environmental consequences, these underutilized but economically valuable discards or by-products with remarkable biochemical activity are being reprocessed as well as valorised to produce nutraceuticals, bioactive derivatives, chitosan and oligomers, natural pigments and so on (Hamed et al. 2016; Shahidi et al. 2019), with improved functional qualities as well as a wider range of applications.

PUFA production for processing fishery by-products

PUFAs, particularly eicosapentaenoic acid (EPA; 20:5*n*-3) and docosahexaenoic acid (DHA; 22:6*n*-3), have been recognized for their essential biochemical function in wellness, particularly in the protection as well as treatment of a variety of human disorders (Sahena et al. 2009). Similar to this, the shortage of linoleic acid (LA; 18:2*n*-6), an important fatty acid (FA), inside the diet is to blame for the emergence of anomalies including diabetic neuropathy, rheumatoid arthritis, reproductive and autoimmune illnesses (Kinsella 1986; Simopoulos 1997). The creation of PUFA concentrates employs a variety of techniques (Rubio-Rodríguez et al. 2010). The technology involves a supercritical fluid extractor, where the separation is based mostly on molecular weights (Mishra et al. 1993). Because of the steric interference brought on by both five and six double bindings, correspondingly, the enzymes used in the enzymatic approach (Shimada et al. 2001) are unable to hydrolyze the ester bonds of EPA and DHA. According to Guil-Guerrero and Belarbi (2001), urea complex formation is a quick and effective method that utilizes the degree of uniformity in FA's structure and aids in separation by becoming entrapped as a guest molecule inside the urea complexes. Because the existence includes all cis links, saturated as well as monounsaturated FAs have an almost straight shape and may therefore be quickly entrapped by the cavity of the urea complexes, but unsaturated FA is a non-linear molecule (Iverson and Weik 1967).

Utilization of waste as biofuel

Wet biomass is an end-up waste product of industrial procedures that can be found in abundance. This waste needs to be disposed of, and finding the best solution to do so requires looking into all available options as well as environmental protection. The thermal recycling of leftovers as secondary fuels is becoming more and more interesting to power station management (Arvanitoyannis and Ladas 2008). As one of the greatest potential species for biodiesel production, Indian oil sardines have a high fat content. These studies indicate that an optimum transesterification employing potassium hydroxide (KOH) at 1500 C and atmospheric pressure were discovered. With 1.25% KOH and 20% methanol and a 25-min reaction period, the best production of 96.57% biofuel was produced (Kumar et al. 2019). Although Indian oil sardines produce higher-quality biofuel, it is not recommended to use them in the process because they are an important source of crucial fatty acids, protein as well as other key nutrients. For the purpose of producing Indian oil sardine-based biofuel, increased efforts are required to gather trash from various sectors, especially industries, retail stores, marketplaces and families (Verma et al. 2020). The use of this biofuel (dry sludge) for something like steam production had demonstrated to be an effective alternative because of hygienic, environmental as well as operational issues associated with the discharges, land disposal and re-use of waste materials. Both excellent heat capacity and sustainable energy are characteristics of that kind of fuel source. The 4:1 biofuel-to-sawdust proportion used in the combustion trial satisfied overall essential specifications for characterizing this prospective fuel, but optimal operating characteristics are still needed to keep nitrogen dioxide as well as sulphur dioxide emissions within regional and/or global restrictions. Diesel fuel made from petroleum can be replaced with or combined with biodiesel fuel made from either the fats or oils of livestock as well as fish. There is a wealth of information available on the manufacture of biogas from cow dung, pig effluent as well as fish farming leftovers (Arvanitoyannis and Kassaveti 2008).

Pigment from seafood processing by-products

Carotenoids are the main pigmentation present in the by-products from the processing of seafood. Shellfish by-products and discards, notably particularly invertebrates like shrimp, lobsters, crabs, crayfish as well as krill, are significant sources of naturally occurring carotenoids, primarily astaxanthin (Sachindra et al. 2007; Sawmya and Sachindra 2015). Potential economic uses as a source of colouration in fish farming exist for the carotenoids recovered via crustacean waste or by-products. Carotenoids are also employed as colouring agents in food, medicine as well as cosmetics in addition to being utilized in aquaculture feeds (Sachindra et al. 2011). The estimated value of the carotenoid compounds marketed worldwide is 935 million US dollars (Fraser and Bramley 2004). To give egg whites of different egg production species a desired colour, carotenoid compounds also have been added to poultry diets (Suresh and Prabhu 2013).

Conclusion

The industrialized seafood processing generates a significant amount of non-edible by-products and waste each year. Using seafood by-products or waste to create high-value commodities could thus be an efficient way to sustainably harness untapped seafood resources while minimising environmental consequences. To reduce the amount of waste discarded by the fish industry, several strategies have been tried. Traditional methods for using seafood by-products or discards include fish meal, fish oil, fertiliser or manure, fish silage, fish sauce and protein hydrolysates. Despite the fact that many diverse items have been created as a result of widespread processing of seafood by-products or waste, their commercial worth is very low, discouraging the use of seafood by-products or waste by applying these technologies in many countries around the world. As an alternative, the synthesis of many high-value-added goods, such as oils, amino acids, mineral resources, collagen, chitin, chitosan, enzymes, bioactive peptides and gelatin, could be accomplished using waste from the seafood industry as raw material. Recent biotechnology advances have altered people's perceptions of by-products and waste from seafood processing. These advancements include the identification of biologically important product offerings as well as their potential application in expanding industries such as functional food, affordable healthcare, nutraceuticals and beauty products. Thorough investigations of identified naturally occurring substances, as well as the development of optimal, financially feasible and also sustainable processing technologies, will facilitate a successful journey of seafood processing by-products and discards throughout the nourishment and pharmaceutical areas.

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Data availability Data and materials associated with the work are available upon request.

Declarations

Consent to participate The corresponding author certifies that the other co-authors actively contributed to the project work and signed the "Participant consent form" on their behalf.

Consent for publication The corresponding author, on behalf of all the authors, gives the publisher permission to publish the submitted work's content (including text, figures and data).

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