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Implementing fermentation technology for comprehensive valorisation of seafood processing by-products: A critical review on recovering valuable nutrients and enhancing utilisation

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ABSTRACT

Fermentation technology is a biorefining tool that has been used in various industrial processes to recover valuable nutrients from different side streams. One promising application of this technique is in the reclamation of nutritional components from seafood side streams. Seafood processing generates significant amounts of waste, including heads, shells, and other side streams. These side streams contain high quantities of valued nutritional components that can be extracted using fermentation technology. The fermentation technology engages the application of microorganisms to convert the side stream into valuable products like biofuels, enzymes, and animal feed. Natural polymers such as chitin and chitosan have various purposes in the food, medicinal, and agricultural industry. Another example is the fish protein hydrolysates (FPH) from seafood side streams. FPHs are protein-rich powders which could be used in animal nutrition and nutraceutical industry. The resulting hydrolysate is further filtered and dried resulting in a FPH powder. Fermentation technology holds great possibility in the recovery of valuable nutrients from seafood side streams. The process can help reduce waste and generate new value-added products from what would otherwise be considered a waste product. With further research and development, fermentation technology can become a key tool in the biorefining industry.

KEYWORDS

Animal nutrition; bioactive peptides; biorefinery; fermentation; nutrient recovery

Introduction

The fast increase in the world's population, which is anticipated to reach more than 9 billion people by 2050, will cause a major increase in the need for food (Karimi et al. 2021). Conversely, when individuals get more affluent, there is an increased demand for premium food and other products. Nevertheless, food resources, particularly captured, will be limited (Välímää et al. 2019). The aquatic ecology, which is very diverse, provides around 20% of global food (Sharma et al. 2020). Additionally, it contains millions of species containing nutrients and bioactive compounds that are little explored but could have high added value for food, pharmaceuticals, and cosmetics (Ucak et al. 2021). By 2030, 183 million tons of seafood are anticipated to be needed for human sustenance (Sharma et al. 2020). The seafood industry produces significant amounts of processing discards, such as heads, viscera, scales, and bones, which make up approximately 40–60% of

the weight of raw materials (Singh et al. 2022). Consequently, seafood generally has a lower usable mass and produces more side streams (Sharma et al. 2020). Proper disposal of such products is still a major issue since their discharge might result in significant environmental risks that adversely affect the aquaculture and fishing sectors (Marti-Quijal et al. 2020; Ucak et al. 2021). According to research, by-catch and discards from seafood processing are abundant in a variety of biologically and nutritionally significant protein components, and lipids with high amounts of poly unsaturated fatty acids (PUFA), minerals, gelatin, collagen, and carotenoids (Singh et al. 2022; Ucak et al. 2021; Välímää et al. 2019). These side streams should be given a second chance in order to prevent pollution and improve the fishing and aquaculture industries, in addition to supplying many vital nutritional and functional components (Marti-Quijal et al. 2020). The presence of bioactive and health-promoting components makes it possible to develop applications for healthy foods, nutrients, and special

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feeds in addition to technologies other than food, such as cosmetics (Singh et al. 2022; Välimaa et al. 2019). Consumers are adopting a health-conscious lifestyle, which supports this trend. It is also possible to create a positive image for new products derived from the by-product due to increased consumer awareness of environmental issues (Välimaa et al. 2019). Furthermore, the European Union (EU) Commission proposed the Green Deal in 2020, promoting a circular economy as a social goal and an innovative development model (Donzella et al. 2022; Leong et al. 2021). Sustainable product design, consumer empowerment, and rotation in production processes are all discussed in this central document. Another idea is to develop an industry for secondary raw materials. These are side streams that are often thrown away as trash but may instead be reused as raw materials. Identifying alternatives to supply chains has the dual goal of reducing side streams and environmental problems (Allegretti et al. 2022). As a result, functional foods, nutrient supplements, pharmaceuticals, and cosmetics can be developed at a low cost. Furthermore, using side streams and low-value seafood efficiently and rationally can help improve sustainable and environmentally friendly production (González-Camejo et al. 2023; Ucak et al. 2021). Current economic dynamics require more sustainable and renewable technologies to maximize resource recovery from side streams. Recent years have seen the development of several new processing techniques for improving nutritional quality and microbial safety while additionally increasing food physicochemical properties by reducing process intensity, decreasing energy usage, reducing side streams loads, and enhancing process productivity and production. Although these advantages are undeniable, in some instances, the cost of using innovative technologies and the dependence on them pose obstacles. Under these circumstances, microbial fermentation or enzymatic hydrolysis are frequently used as bioconversion procedures (Singh et al. 2022). Green techniques are anticipated to displace traditional technologies for extracting resources from food side streams in the future due to their simplicity of use and environmental safety (Venugopal and Sasidharan 2022). In recent years, “green chemistry” has grown in popularity, which relies on creating and improving green extracting processes that use microorganisms and enzymes to recover bioactive substances side streams from seafood (Singh et al. 2022). Biorefining based on green chemistry is secure, effective, and ecologically responsible since it doesn't compromise the extracted chemicals' inherent qualities (Venugopal and Sasidharan 2022). By-products of the seafood industry can be valorized through biorefining to increase their value as biomaterials and energy sources (Singh et al. 2022). Green technologies can demonstrate promising performance for the recovery of bioactive compounds when assessed with established considering the efficiency, energy efficiency, and cost effectiveness (Venugopal and Sasidharan 2022). Chemical extraction, which uses strong acids and alkalis at high temperatures, is widely used. These conditions require more energy and are associated with disadvantages such as being time-consuming, having higher treatment costs, requiring a large volume of water (to neutralize and wash acids and alkalis), and having worse properties (physical and chemical)

of the obtained product. Recent developments in the seafood processing industry have introduced biotechnology processes, such as bio catalysis and fermentation, that could be applied to recover valuable components (Singh et al. 2022; Venugopal and Sasidharan 2022). The food, energy, pharmaceutical, and side stream treatment industries are all paying attention to fermentation since it has less effect on the environment and lower operating costs than traditional chemical processes (Chai et al. 2022). Therefore, integrating biological processing facilities and implementing innovation-based exploitation methods can maximize resource recovery by creating a bioeconomy (Singh et al. 2022). Incorporating green chemistry into industries related to the ocean can lead to a more profitable, sustainable, and conscious ocean economy (Venugopal and Sasidharan 2022). This study investigates the significance of fermentation processes used in biorefining to recover high-value resources involving protein, lipids, and bioactive peptides, as well as different fermentation strategies used to transform seafood by-products.

Significance of fermentation as a resource recovery tool

Preventive measures can reduce the production of inedible food side streams at every step, from production to utilization. For this scenario, there is an urgent requirement for suitable side streams management policies (Dahiya et al. 2018). Physical, chemical, and biological processes are often used in side stream treatment techniques, alone or in combination. Physical and chemical processes are often harsher and less ecological than biological processes like fermentation or enzymatic hydrolysis (Rai et al. 2011 Siddiqui et al., 2023). Conventional methods for valorizing discarded materials and seafood side streams depend on physical and chemical methods. There are always various restrictions to these processes, and these shortcomings have increased interest in greener alternatives, such as biorefineries (Venugopal and Sasidharan 2022).

The role of biorefineries in the valorization of seafood by-products

Biotechnology promises to produce goods with added value, ensure product quality, and develop new techniques for getting rid of side streams for recovering resources. Such methods have been made possible by new green technologies for industrial biomolecule recycling from side stream materials and seafood products (Venugopal 2021). Recovery using green process is possible; among the sources are microbial fermentation, enzymatic reactions, methanogenesis, photosynthesis and oil processing. (Venugopal and Sasidharan 2022). Biological procedures can be affordable, secure, and have little to no detrimental impact on the characteristics of isolated components. Consequently, these procedures offer a flexible and affordable method of concentrating side streams and effluent water into useful goods (Venugopal 2021). In particular, for the biorefinery, which seeks to increase the use of aquatic resources through the recovery of materials connected to seafood residues,

resulting in production and addressing activities that enhance marine values (Veríssimo et al. 2021). By incorporating the biorefinery concept into the marine industry, it is possible to preserve natural resources and eliminate the production of seafood side streams while simultaneously generating employment and increasing profits. Side streams from fish processing may provide biorefineries with a viable renewable biomass source. Under the biorefineries method, value-added goods including industrial chemicals, biofuels, animal feed, organic fertilizers, nutrients, etc. are produced from fish side streams. Some key aspects of the process are low cost and ease of use, which are achieved by lowering labor costs, energy usage, and material costs while maintaining high production (Venugopal 2021). A complex matrix of macromolecules, natural polymers, and minerals makes up seafood side streams. As a result, the process of extracting by-products from these residues often involves several steps and separation processes. Depending on the traits and qualities provided by the new target components, as well as the required level of purity of the commercial goods, the extraction platform's design will change (Veríssimo et al. 2021). Modern biorefineries are built exceptionally cost-effective and can handle untreated and dangerous source materials (such as industrial, residential, and agricultural side streams) while generating safe outputs (Venugopal 2021). A blue ocean economy is becoming a reality, thanks to significant advancements. Yet, we can only create a whole marine biorefinery when we combine each of these processes into a seamless and efficient production system (Veríssimo et al. 2021). The type and accessibility of raw materials will determine the amount of fuel that any biorefinery technology can generate. Consequently, if these technologies can be coupled under the integrated concept of side streams biorefining, mixed and diverse raw materials may be processed to generate many materials like power, food, heat, feed, and energy together with chemical products with added value (Nizami et al. 2017). By using biological treatment methods, side streams can be processed

more effectively, and a variety of products, including biofuels (hydrogen, methane, and bioethanol), biomaterials, platform chemicals, biofertilizers, animal feed, biomass, and bioelectricity can be produced.

Microbial fermentation to recover valuable biomolecules

Due to its safety, energy production, lower environmental impact, and lower operating costs compared to chemical processes, fermentation has gained the interest of the food processing, pharmaceutical energy, and side streams treatment industries. It is described as the process of any natural substance reacting by means of microbial activity, which is facilitated by a range of enzymes (Chai et al. 2022; W. Sun, Shahrajabian, and Lin 2022). The use of fermentation can provide various advantages concerning hydrolysis by pH changes and has also been used for several years to produce valuable products from various side streams (Marti-Quijal et al. 2020; Venugopal and Sasidharan 2022). Fermentation is a biotechnological process that humans have been doing since ancient times. Today, many chemicals are manufactured using fermentation technology, which plays a significant role in industrial production. Living microorganisms (fungi, mycelium, bacteria, or microalgae) use raw resources in this procedure to produce high-quality goods (Venugopal 2021). Fermentation, in general, is an enzyme-driven process that breaks down complex organic compounds into simpler ones, like glucose, without oxygen. Less energy is produced during fermentation than during aerobic cellular respiration, which produces two ATP molecules. Depending on the organism, fermentation can produce a variety of other by-products. During fermentation, lactic acid, lactate, carbon dioxide (CO_2), and water are produced by bacteria, fungi, protozoa, and animal cells. In yeast and even most plant cells, fermentation results in the production of ethyl alcohol, CO_2 , and water. Fermentation has also been utilized recently to produce valuable products from multiple side streams (Venugopal and Sasidharan 2022). The categorization of

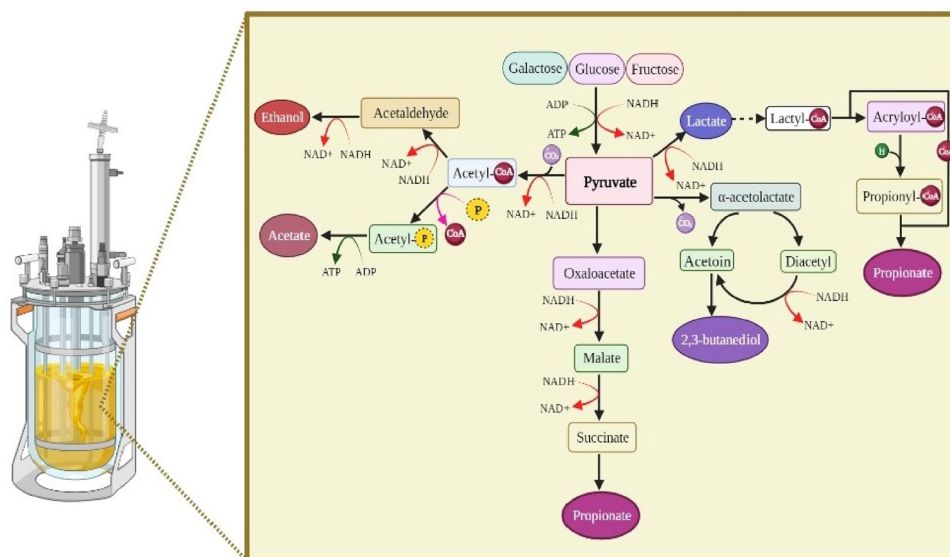


Figure 1. The mechanism of various fermentations.

fermentation technologies is shown schematically in [Figure 1](#). The process of fermentation involves employing an endogenous electron acceptor, which is often an organic substance, to oxidize organic materials like carbohydrates in order to produce energy. The kinds might be conventional, biomass, or precise. Traditional fermentation has existed for thousands of years. Biomass fermentation has been employed in the food business since the 1980s to create cell mass that can be utilized as nutrients, biomaterials, enzymes, flavorings, fuel, and medicines. More recently, it has become a source of alternative proteins for the creation of cultured meat compositions ([Venugopal 2021](#)). Technology for microbial transformation offers an efficient method for isolating and using promising biotechnological substances ([Dahiya et al. 2018](#); [Venugopal 2021](#)). Bacteria, fungi, and protozoa are examples of the microorganisms utilized for this function, which can be facultative, anaerobic, or aerobic. Anaerobic, batch, continuous, or fed-batch microbial fermentation processes are all possible in solid, submerged, or liquid media. By adding continuous or pulsed medium cultures until the desired volume is reached, fed-batch devices are frequently used to produce organic acids, ethanol, microbial biomass, enzymes, antibiotics, vitamins, and other compounds. Higher productivity, greater dissolved oxygen levels in the environment, better biodegradation rates, and shorter fermentation times are benefits of fed-batch processes over traditional non-continuous ones ([Venugopal 2021](#)). Compared to other biological platforms, anaerobic fermentation is attracting a lot of interest for the generation of biofuels and environmental chemicals from biogenic side streams, particularly food side streams ([Dahiya et al. 2018](#)). The fermentation of lactic acid bacteria (LAB) is a common technique for creating fermented fishery products ([Venugopal 2021](#)). Microbial fermentation using organisms generally recognized as safe has several commercial advantages. Now, this new initiative in the EU includes a minimum of 400 manufacturers ([Nizami et al. 2017](#)). Positive news is that sales of fortified/functional foods have increased dramatically globally in recent years, according to Euromonitor ([Venugopal and Sasidharan 2022](#)). By 2027, a large increase in the market for fish protein hydrolysis is anticipated. Fermentation has been used in recent years to transform various side streams into valuable products ([Venugopal and Sasidharan 2022](#)). Bioremediation of food side streams may supplement fossil-based remediation to some extent and address important drivers of the bioeconomy, resource security, ecosystem services, and climate by creating a wide variety of bio-based end products, including biofuels, product chemicals, and biological fertilizers. By biologically treating food side streams, we will soon achieve a sustainable path with minimal environmental effect ([Dahiya et al. 2018](#)).

Lactic acid fermentation to recover biomolecules

Researchers have looked at how LAB affects side streams stabilization and biomolecule recovery from side streams generated from animal and fish processing sectors ([Coimbra 2016](#); [Kumar et al. 2018](#); [Marti-Quijal et al. 2020](#); [Vázquez et al. 2019](#)). Lactic acid fermentation is gaining popularity in the case of side streams since it is an ecologically acceptable

process that produces a product that can be used straight as feed or as a neutralizer ([Marti-Quijal et al. 2020](#)). For example, extracting biomolecules from the processing of seafood side streams requires controlled fermentation. LAB fermentation has a greater impact than the acid approach. These microorganisms produce numerous compounds like diacetyl hydrogen peroxide, organic acids, and bacteriocins. They have a substantial effect on inhibiting spoilage microorganisms and improving food taste and texture. Commercial LAB strains are essential for the food and edible industries to benefit from fermentation ([Özyurt et al. 2017](#)). The kind of organism, the amount of inoculum, the pH at the beginning and during fermentation all have an impact on the formation of lactic acid. Lactic acid, which is created when sugar is broken down, causes a low pH, which reduces the development of bacteria and encourages the activity of acid proteases. These enzymes function best on the proteins found in seafood, many of which are chitin-, carotenoids-, and lipid-attached ([Venugopal 2021](#)). Fish and by-products from slaughterhouses have been successfully preserved using LAB fermentation ([Marti-Quijal et al. 2020](#)). The addition of an acceptable quantity of fermentable carbohydrates, decreasing the pH during fermentation and while storing the finished product, quick growth of the starting culture, and enough lactic acid generation are the three primary requirements for effective lactic acid fermentation. In 24 to 48h, or even 3.9 in certain circumstances, a mixture of fish or animal by-products, carbohydrates, and a starting culture can ferment to produce a pH level ranging from 4.4 to 5.0. When the fermentation process of slaughter by-products becomes successful, the pH should be below 5.0 and remain there for less than one year. Fish fermentation, a common method for extending shelf life, creates the necessary bacterial metabolites. The generation of antioxidant chemicals, oil, and protein hydrolysates are all improved by fermentation in by-products ([Marti-Quijal et al. 2020](#)). LAB has long been used to create fermented fish products. Acidic proteases that work on proteins, lipids, and carotenoids that are bound to chitin are more active when the pH is low ([Venugopal 2021](#)). Fermentation can offer a number of benefits for hydrolysis by causing pH shifts. Among several of the principal advantages, fermentation boosts the efficacy of antioxidant peptides associated with glutathione to prevent oxidative stress damage. In addition, fermentation, which hydrolyzes and decomposes proteins to peptides and shorter amino acids, produces better digestible proteins when used as animal feed protein source. This makes it an excellent tool for enhancing fish nutritional content. In comparison to formic acid treatment, fermentation improves fish side streams oil quality ([Marti-Quijal et al. 2020](#)). Fermentation may thus result in the production of a variety of value added products, including enzymes, cell mass, flavors, and food additives. Fermentations brought on by LAB also result in a diversity of foods, which turn in edibles into edibles, preserve food, boost nutritional value, lower toxicity, and require less cooking time and energy ([Venugopal 2021](#)). This technique is advantageous, safe, and good for the environment. It offers the possibility of obtaining a wide range of compounds, in addition to not consuming much energy ([Marti-Quijal et al. 2020](#); [Venugopal 2021](#)).

Various applications of biomolecules obtained from seafood by-products

Pigments, chitin, lipids, and proteins found in seafood offal can be recovered or used as inexpensive substrates to make a range of bioproducts (Veríssimo et al. 2021). Fish by-product fermentation results in high-quality proteins, oil, and antioxidants. The fermented product can be used as a nutrient for aquatic animals (Venugopal 2021). Also, fish side streams contain compounds rich in nitrogen, phosphorus, and calcium, which are suitable for preparing fertilizer. These fertilizers are currently available on the market and approved for organic farming (Marti-Quijal et al. 2020). With the help of a variety of microorganisms, it was possible to convert fish side streams into liquid fertilizer. This material demonstrated decay resistance for up to six months at room temperature (Venugopal 2021). Most often, a preliminary pretreatment is applied to these substrates in order to transform them into cultivable raw materials. The use of this pretreated solid product, which is rich in calcium, nitrogen, and phosphate, has helped tomato harvests, biopharming, and ice lettuce (*Lactuca sativa* L.) crops. On the other hand, culture experiments commonly use the nutrient-rich blue liquid supernatant as a starting medium to produce a variety of biomolecules. (Veríssimo et al. 2021). Rashid, Jung, and Kim (2018) used *Bacillus cereus* to ferment shrimp shell powder to create sugars, antioxidants, and DNA-protective chemicals. Higher results were reported when comparing fed-batch fermentation to batch biological degradation (Rashid, Jung, and Kim 2018; Venugopal 2021). At STP conditions, 1 kg of food side streams can generate 385 g of propionic acid, 916 g of butyric acid, and 624.96 g of acetic acid (Dahiya et al. 2018; Nizami et al. 2017). In addition to biological molecules, energy can also be obtained from the by-products of marine products. Food side streams at the STP has a calorific value of 5350 KJ/kg, suggesting that it has the prospective to be used as a resource of bioenergy. One gram of glucose should completely oxidize to provide 16 KJ of energy. At a conversion efficiency of 50%, one kg of COD from food side streams produces 15.62 mol of methanol (350 L methanol), which results in 13,882 KJ of energy production and 3.85 kWh of power production (Dahiya et al. 2018). The growth of the bioeconomy and environmental sustainability can both be considerably aided by the usage of energy-intensive and economically viable goods made from food side streams. Also, combining several methods in order to maximize resource recovery with co-production lessens the detrimental effects of food side streams on the environment to a certain level (Dahiya et al. 2018). Table 1 summarizes some other possible uses for fermentation technology.

Application of fermentation technology for recovery of protein from seafood side streams

Among the six essential nutrients for life, protein is a crucial bioactive molecule (Mao et al. 2017). Living organisms require nutrients, proteins, and bioactive peptides to grow and develop (Ucak et al. 2021; Välimaa et al. 2019). To supply protein demand, sustainable approaches are needed.

Promoting biodiversity in food production systems, creating substitute proteins through regenerative methods, and recovering wholesome and sustainable proteins from side streams are a few of these. Proteins may be found in food side streams, particularly seafood (Ucak et al. 2021). The basic protein content of fish side stream varies from 8 to 35%, based on the type of process and fish (Vicente et al. 2022). From seafood by-products, biologically active compounds may be isolated, including hydrolyzed proteins and bioactive peptides including components like, bone, internal organs, and collagen (Mao et al. 2017; Ucak et al. 2021).

Fermentation is an environmentally friendly, and economic method used in a wide range of applications throughout the past century. Fermentation produces a variety of valuable compounds, including proteins (Marti-Quijal et al. 2020). Proteins extracted from fermentation seafood side streams contain essential and non-essential amino acids (Mao et al. 2017; Ucak et al. 2021). They have comparable nutritional value to meat and egg proteins (Ucak et al. 2021). Seafood side streams contain various protein compounds that can be recovered by fermentation and used for numerous applications. Hydrolysis of muscle proteins can result in bioactive peptides with physiological and technical qualities beneficial in the food and pharmaceutical sector (Ucak et al. 2021). Gelatin has applications in protein-based composite biomaterials such as films, emulsions, fibers, foams, hydrogels, and furthermore. Due to their distinct structural and functional properties, fish collagen and gelatin are employed in the therapeutic, biomedical, cosmetic, and biotechnology sectors. They may be employed as food emulsifiers, foaming agents, stabilizers, nutritional microencapsulates, and to improve the sensory qualities of low-fat meals (Venugopal and Sasidharan 2022). In addition, These proteins regulate the metabolism of glucose, have favorable effects on lipid profiles, and control blood pressure, among other beneficial metabolic effects (Ucak et al. 2021). Instead of conventional fermentation, these advancements employ "biomass fermentation." Backbone fermentation is a brand-new alternative protein being researched and released on the market. Depending on the microorganism, fermentation can lead to the manufacture of hydrolytic enzymes (proteases, lipases and chitinases), as well as other enzymes. Microbial fermentation, which uses fish side streams as a carbon-nitrogen source, is an economic, secure, and environmentally friendly method of extracting a varied extent of useful materials from seafood side streams (Venugopal and Sasidharan 2022). Biomolecule recovery requires the employment of nonpathogenic bacterial enzymes (Rai et al. 2011). These microorganisms release hydrolytic enzymes, which break down specific source material constituents to create hydrolysates (Figure 2) (Gao et al. 2021). As opposed to proteases derived from other sources, microbial proteases generated by various microorganisms offer several benefits. They include inexpensive production costs, the potential for mass production, quicker enzyme isolation times, and the capacity of organisms to respond to genetic engineering that increases enzyme effectiveness. *Bacillus* spp., *Bifidobacterium* spp., and lactic acid bacteria are the most frequently used microbial proteases (Godinho et al. 2016). Proteases demineralize and

Table 1. Fermentation technologies for potential application.

Type of fermentation	Substrate	Organisms involved	Conditions/machinery	Advantages	Disadvantages	Reference
1 Alcoholic fermentation	Shrimp shell	<i>Thermomyces lanuginosus</i> MTCC 9331	Prepared media (colloidal chitin (made from chitin flakes), yeast extract, K_2HPO_4 , KH_2PO_4 , KCl, and NH_4Cl , $MgSO_4 \cdot 7H_2O$) (pH 6.5), inoculated (5%), and incubated (50 °C, 6 days, 150rpm).	<ul style="list-style-type: none"> Chitinase production Side streams treatment Low energy consumption 	<ul style="list-style-type: none"> Using chemical treatment to extract chitin (substrate for chitinase production) High capital and operational cost 	(Suryawanshi and Eswari 2022)
2 Lactic acid fermentation	Sea bass (<i>Dicentrarchus labrax</i>)	<i>Streptococcus</i> spp., <i>Enterococcus gallinarum</i> , <i>Lactobacillus plantarum</i> , <i>Pediococcus acidilactici</i> , and <i>Lactobacillus brevis</i>	Mincing sea bass, added molasses (15%), inoculated with LAB strains (5×10^8 CFU/mL), added butylated hydroxytoluene and potassium sorbate, stored (27 °C) in plastic jars with caps, stirred until ripening (daily), added maltodextrin (DE: 18–20) (1:1 (w/w, on dry basis), dried by spray dried (inlet: 160 °C and outlet: 90 °C), aspiration (30 m ³ /h, 20 mL/min) and kept at 4 °C.	<ul style="list-style-type: none"> Fish silage production as feed animals Very digestible and beneficial feed sources Significant use of the energy source Inhibition of the growth of spoilage microorganism 	<ul style="list-style-type: none"> Relatively long fermentation time Fermentation leads to an increase in lipid oxidation. Reduction of essential/non-essential amino acid ratio in fermented fish silage powders during ensiling 	(Özyurt et al. 2017)
3 Alcoholic fermentation	Shrimp Shell Side streams	<i>Pseudomonas</i> <i>antitumoralis</i> 18D36-A1	Control: Included formic acid (3%) Isolated of actinomycetes from marine organisms using dilution method on chitin colloid agar medium (1%), cultured of isolated actinomycetes (7 days), extracted of biodegradation products of oligomers using water and instrumental analysis of shrimp shell biodegradation extract.	<ul style="list-style-type: none"> Using shrimp shell side streams to produce beneficial chemicals. Production of several oligomeric components Capable of producing chitoooligosaccharides from chitin. Inhibit the growth of fungi by 74% (1 mg/mL) by active fraction d36a1C38 	<ul style="list-style-type: none"> Production of a gross product from fermentation that requires further treatment 	(Widyastuti et al. 2022)
4 Lactic acid fermentation	Whole gibel carp whole ponyfish, and seabass processing side streams	<i>Streptococcus</i> spp., <i>Enterococcus gallinarum</i> , <i>Lactobacillus plantarum</i> , <i>Lactobacillus brevis</i> , and <i>Pediococcus acidilactici</i>	Mincing sea food side streams, added 15% molasses, inoculated with LAB strains (5×10^8 CFU/mL), added butylated hydroxytoluene and potassium sorbate, stored (27 °C, 3 weeks) in plastic jars with caps, stirred until ripening (daily), dried by spray dried (inlet: 160 °C and outlet: 90 °C), aspiration (30 m ³ /h, 20 mL/min) and kept at 4 °C. Control: Included formic acid (3%)	<ul style="list-style-type: none"> The prospective inclusion of fermented fish silage (wet and dry form) as a probiotic component and a source of protein in animal feed. Unlike acid silage, starting culture used to prepare silage is not delayed. Creation of superior animal feed Prevents the dumping of fish trash or discards. Increasing digestibility of fermented fish silage 	<ul style="list-style-type: none"> Limitation in the selection of bacterial strains for fish silage production The potential for the development of biogenic amines in fermented foods After fermentation, <i>Carassius gibelio</i>, spermidine, putrescine, histamine, cadaverine, and spermidine levels in wet silage of seabass by-products increased. The trimethylamine value increased significantly following the ensilage procedure. 	(Özyurt et al. 2017)

Type of fermentation	Substrate	Organisms involved	Conditions/machinery	Advantages	Disadvantages	Reference
5 Alcoholic fermentation	Shrimp side streams	<i>Paenibacillus</i> sp. AD	Inoculated 1% in medium containing 1% shrimp side streams (24h), incubated (37 °C, 96 h), centrifuged (10,000 rpm, 15 min, 4 °C), used the supernatant, washed pellet, dried (80 °C), chosen the strain (s) with the highest extracellular chitinase activity and the greatest breakdown of shrimp side streams.	<ul style="list-style-type: none"> Complete decomposition of shrimp side streams (99%) under ideal circumstances The production of chitin oligosaccharides and chitinase occurs simultaneously. Use of chitinase in a variety of biotechnological processes Use of prebiotics and therapeutic medicines made of bioactive chitin oligosaccharides. Create a viable economic and commercial process. Ability to use <i>Paenibacillus</i> sp. AD for large-scale bioremediation of seafood side streams 	-	(Kumar et al. 2018)
6 Alcoholic fermentation	Fish solid side streams (FSW)	<i>Bacillus subtilis</i> (KP172548)	Washed FSW, stored (-20 °C), boiled FSW ((1:10 w/v), 50 °C, 20–25 min), filtered supernatants, inoculum (1.5 × 10 ⁸ CFU/mL), procured polyhydroxy butyrate (PHB) production medium (phosphate buffer saline mixed with FSW extract in a 2:1 ratio), standard PHB, poly-lactic acid, and culture media.	<ul style="list-style-type: none"> Side streams treatment. Utilizing different inexpensive substrates for polyhydroxy butyrate production Less toxicity of biocompatibility of produced PHB compared to PLA and commercially available PHB. Desirability of produced PHB for surface attachment and propagation The use of <i>Bacillus subtilis</i> to produce PHB from FSW is a cost-effective and ecologically responsible method. Ability to grow <i>Bacillus</i> species on cheap raw materials. Cost-effectiveness of polyhydroxyalkanoate production 	<ul style="list-style-type: none"> Production of a gross product from fermentation that requires further treatment 	(Mohapatra et al. 2017)
7 Alcoholic fermentation	Shrimp Shell Side streams	<i>Pseudonocardia carboxydivorans</i> 18A1301	Prepared plates of colloidal chitin agar (50% (v/v) artificial seawater, supplemented cycloheximide (25 µg/mL), and nalidixic acid (25 µg/mL)), cultured (28 °C, 14 days), isolated <i>Actinomycetes</i> , purified on shrimp shell media nourished with 1% colloidal chitin in 50% (v/v) agar/seawater, streaked the purified isolate on slants of 1% colloidal chitin agar (4 °C, and in glycerol 20% (v/v), -20 °C).	<ul style="list-style-type: none"> The potential of marine actinomycetes to grow on shrimp shell as a substrate, adding value to innovative products. Production of bioactive secondary metabolites and <i>staphylococcus aureus</i> growth inhibition (minimum inhibition concentration: 15.6 µg/mL) Side streams treatment and production of valuable products 	<ul style="list-style-type: none"> Production of a gross product from fermentation that requires further treatment 	(Setiawan et al. 2021)

(Continued)

Table 1. Continued.

Type of fermentation	Substrate	Organisms involved	Conditions/machinery	Advantages	Disadvantages	Reference
8 Alcoholic fermentation	Different kinds of shrimp side streams	<i>Paenibacillus elgii</i> TKU051	Grown <i>P. elgii</i> in a flask containing the liquid medium (1% each kind of shrimp side streams, 0.1% K ₂ HPO ₄ , 0.05% MgSO ₄ ·7H ₂ O, w/v) (37°C, 150rpm, 7 days). Control: without inoculated	<ul style="list-style-type: none"> Comparable effect of chitin obtained with commercial chitin on Congo Red absorption (approximately 90%) Increasing the economic value of products Avoid contaminating your samples with acids or alkalis used for demineralization or deproteinization. The crude enzyme cocktail produced by <i>P. elgii</i> exhibits anti-glucosidase and antioxidant activities. Inhibiting properties High protein degradation efficiency of <i>P. elgii</i> in various shrimp side streams (more than 94%). Ability of <i>P. elgii</i> to produce proteases and chitin from chitin fishery byproducts. Microbial protease is an environmentally friendly way to remove protein. 	<ul style="list-style-type: none"> Production of a gross product from fermentation that requires further treatment 	(D.-H. Lee et al. 2021)
9 Alcoholic fermentation	Tuna Fish Side streams (<i>Katsuwonus pelamis</i>)	<i>Bacillus subtilis</i> ATCC 21332	Conducted with a series of concentrations (20, 30, 40, 50, and 60 (g/L)), added Key supplement minerals (5 × 10 ⁻⁴ FeSO ₄ and 0.15 MnSO ₄ (g/L)), added distilled water into each Erlenmeyer flask, inoculum 2% (v/v), incubated (30°C, 7 days, 130rpm), centrifuged (8000 g, 10 min), collected.	<ul style="list-style-type: none"> Cost-effective and Economical biosurfactant (surfactin) production Assist the local factories in eliminating side streams rubbish and effluent water pollution. Industrialization of surfactin was enabled by understanding its metabolic mechanism and production kinetics. 	<ul style="list-style-type: none"> Further effort will be required to improve the whole fish side streams substrate with the right amount of carbon or nitrogen supply. 	(Hu et al. 2021)
10 Propionic acid fermentation	Gibel carp fishes, Klunzinger's and ponyfish sea bass by-products	<i>Lactobacillus brevis</i> , <i>Streptococcus</i> spp, <i>Enterococcus gallinarum</i> , <i>Lactobacillus plantarum</i> , and <i>Pediococcus acidilactici</i> ,	Mined Fish-based samples (3 mm mesh), added Molasses (15%, molasses/fish and 5% vLAB/ fish), inoculated (10 ⁸ CFU/mL), added potassium sorbate and butylated hydroxytoluene, created anaerobic conditions, stirred by hand (4–5 min, daily (21 days)), added maltodextrin from hydrolyzed corn starch (1:1 (w/w)), dried some silages (spray dried, inlet: 160°C and outlet: 90°C, 30 m ² /h, 20 mL/min), mixed and packed into a light-protective plastic bottle, stored at 4°C. Control: Use formic acid (3%, v/v) to acidify silage.	<ul style="list-style-type: none"> Fermented silages produced lactic and propionic acids. Significant ability of LAB strains to synthesize propionic acid from carp silage. Significantly higher organic acid content in spray-dried fermented silage than in wet fermentation The greatest amounts of propionic acid buildup were seen in the gibel carp silage fermented with <i>L. plantarum</i>. Fermentation of fish-based silages can create organic acids due to the presence of lactic acid bacteria strains. Wet and spray-dried fish-based silages provide high food safety and quality for animal feed. 	<ul style="list-style-type: none"> Production of a gross product from fermentation that requires further treatment. Fish silage calls for passable technological expertise. Production fish silage Rely on the improvement and regulation of the environmental, operational, and processing conditions. 	(Kuley et al. 2020)

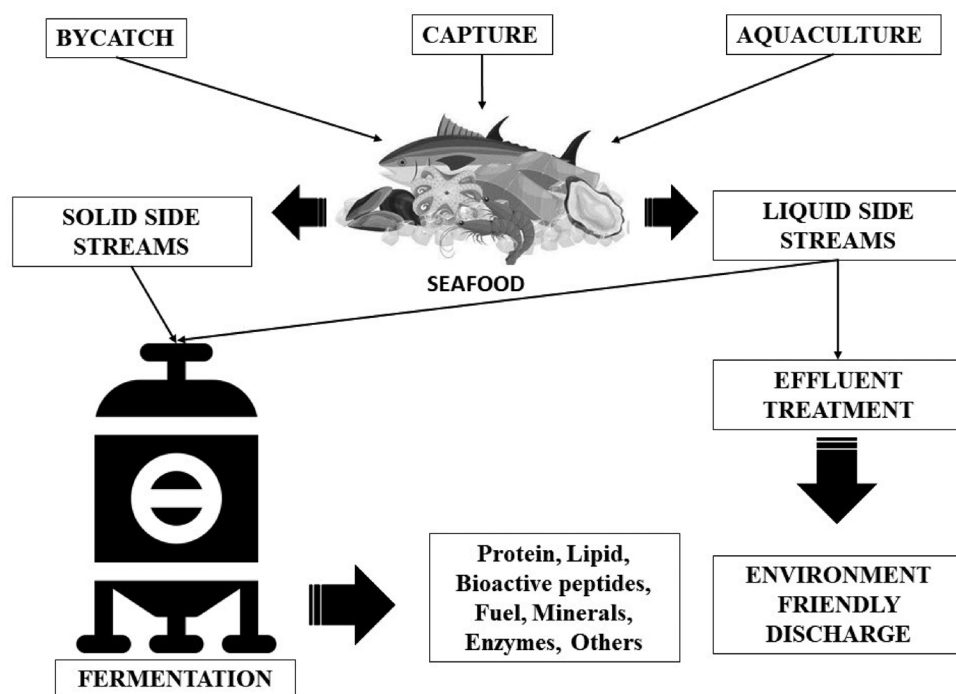


Figure 2. Recovery of valuable material from seafood side streams.

deproteinize food side streams (Ucak et al. 2021). Microorganisms that occur naturally or added to hydrolyze proteins and sugars are required for fermentation. Two growth parameters that influence the production of hydrolyzed proteins are the inoculation circumstances and the peptide content of the medium. Extracellular microbial proteases hydrolyze a broad range of peptides differing in molecular weight and amino acid sequence. These bioactive peptides have fascinating features (Godinho et al. 2016). On the whole, peptides generated from seafood by-products often have biological qualities such as antimicrobial activity, antioxidant activity, antiproliferative impact, antihypertensive activity, anticoagulant action, calcium absorption, bone mineralization, and furthermore (Ucak et al. 2021). Recent studies by several authors have focused on the utilization of microbes to manufacture bioactive peptides through proteolysis (Godinho et al. 2016). Protein hydrolysates produced from fish flesh using A26 were investigated by Jemil et al. (2014) for their functional, antibacterial, and antioxidant properties. It demonstrated the beneficial solubility, emulsification stability, and foaming capabilities of the hydrolyzed proteins generated by fermentation utilizing various fish meat. The proteolytic enzymes of *Bacillus subtilis* A26 produced peptides during the biorefinery of fish proteins that have antioxidant and antibacterial activities (Jemil et al. 2014). In one more study, the result of *Bacillus subtilis* fermentation by means of lactic acid bacteria isolated from freshwater fish head side streams to recover lipids and proteins simultaneously was reported by Ruthu et al. (2014). The findings indicated that fermentation had no impact on fatty acid or lipid profiles. Fish head proteins that are antibacterial and antioxidant may be used as functional additives in food compositions. Hence, it could promote human health and/or lengthen the food's shelf life. The fermented

hydrolyzed protein has shown antibacterial properties against diverse bacterial species. Its usage may be seen in the pharmaceutical business, nutritional supplements, and food preservation (Ruthu et al. 2014). Hydrolysates made from soup fish skin fermentation with *Aspergillus oryzae*, according to Fang et al. (2017), also exhibit strong antioxidant activity. It may be an inexpensive source of antioxidants with a large range of prospective applications in the food and medicinal sectors. These applications include those for food preservation and health promotion (Fang et al. 2017). Finally, fermentation bioprocesses contribute to clean production by minimizing environmental impacts while transforming fish side streams into valuable functional materials. Table 2 shows the different applications of fermentation to enhance the valorizing of seafood by-products. So, it appears certain that fermentation is a method that suggests many options and can be employed to get various compounds of benefits (Marti-Quijal et al. 2020).

Application of fermentation technology for recovery of lipids from seafood side streams

Fermentation could be considered as a suitable means in modifying and improving value of lipid waste. As a result of process of fermentation there is a hydrolyzed protein rich fraction as well as oil and chitin or collagen according to the type of waste. Other than protein from fish industry waste lipid base compounds include fish oil, poly unsaturated fatty acids (PUFA), phospholipids and cholesterol. The fatty acids such as eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA) are well known source of nutritionally valuable component which are by-products/discards from fish processing. The PUFAs have got the advantage of reducing hypertension, risk of cardiovascular disease,

Table 2. Fermentation technologies for recovery of protein from seafood side streams.

	Type of side stream	Fermentation method used	Substrate/organism	Fermentation conditions	Observations	Reference
1	Shrimp head side streams	Solid-state fermentation	White shrimp head (<i>Litopenaeus vannamei</i>) side streams / <i>Lactobacillus futsaii</i> LAB06 and <i>L. Plantarum</i> LAB14	Crushed non-sterilized shrimp heads, mixed with sucrose (10% (w/w)), inoculated (5%) (10^8 CFU/mL), fermented in Erlenmeyer flasks (30°C, 48 h), evaluated bacterial strains alone and in consortium.	<ul style="list-style-type: none"> The highest chitin and protein-rich liquid recovery were made possible by the largest lactic acid generation. 30% of fermented liquor was found to provide the most effective results for Nile tilapia post-larvae health, biomass, growth rate, increase weight, and length gains, leading to economic and environmental benefits. 	(Ximenes et al. 2019)
2	Carp fish side streams	Solid-state fermentation	Indian major carps / <i>Pediococcus acidilactici</i> NCIM5368, <i>Pediococcus acidilactici</i> MW2, <i>Pediococcus acidilactici</i> FM37, and <i>Enterococcus faecalis</i> NCIM5367	Mixed fish visceral side streams of Catla and Rohu (1:1 (w/w)), heated (85°C, 10 min), homogenized, cooked, mixed with salt (2%) and dextrose (10%) (both w/w) by continuous stirring, inoculated LAB (10% (v/w)), placed in a sterile airtight container, incubated (37°C, 48 h).	<ul style="list-style-type: none"> Antioxidant and antagonistic activities against some bacterial pathogens were shown by hydrolyzed protein. The outcomes unequivocally show the value of native isolate fermentation from fish side streams to recover lipids and proteins simultaneously. The results showed Fermentation is an eco-friendly method that reduces the disposal/pollution of solid side streams. 	(Rai et al. 2011)
3	Fish skin	Solid-state fermentation	Nile tilapia (<i>Oreochromis niloticus</i>) skin / <i>Bacillus velezensis</i> FEL-BM21	Placed fish skin tissue and pelleted cells (new seed fluid (15 mL)) in Erlenmeyer flasks (with sterile water), and incubated (20°C, 200 rpm, 12 h).	<ul style="list-style-type: none"> The yields of fermentation-acid-soluble and fermentation-pepsin-soluble collagen were only slightly better than those of chemical-acid-soluble and chemical-pepsin-soluble collagen. Type I collagen was found in every extract, with good preservation of its triple-helical structure. Data showed that all extracts had a triple helix structure and were type I collagen. Due to its biochemical characteristics, fermentation is a practical substitute for pre-treating collagen extraction materials. 	(Song et al. 2021)
4	Freshwater fish head side streams	Solid-state fermentation	Indian major carps/ <i>Enterococcus faecium</i> NCIM5335, <i>Pediococcus acidilactici</i> NCIM5368, and <i>Pediococcus acidilactici</i> FD3	Preparation of silage crushed Fresh water fish heads, homogenized, mixed, cooked under steam, cooling, added salt (2 % (w/w)) and dextrose (10 % (w/w)), mixed, placed (in airtight container), incubated (37°C, 72 h).	<ul style="list-style-type: none"> The method caused the material's proteins to hydrolyze to 38.4%. Antioxidant activity and antagonistic capabilities against bacterial and fungal pathogens were present in the hydrolyzed protein-rich fermentation liquor. <i>Listeria monocytogenes</i> and <i>Salmonella itridicus</i> showed minimum inhibitory values of 10 and 12 mg/mL in fermented liquor using <i>E. faecium</i> as the starter. Fish head-derived antioxidant and antibacterial proteins may be employed in food formulations to enhance shelf life, food preservation, dietary supplements, and the pharmaceutical sector. 	(Ruthu et al. 2014)

(Continued)

Table 2. Continued.

	Type of side stream	Fermentation method used	Substrate/organism	Fermentation conditions	Observations	Reference
5	Fish processing effluent water streams	Submerged fermentation	Four different herring (<i>Clupea harengus</i>)/ <i>Aspergillus oryzae</i> var. <i>oryzae</i> CBS 819.72	Placed medium in Erlenmeyer flasks (sludge, effluent water, end-of-pipe, salt brine, or a mixture of effluent water and sludge), inoculated (1.69×10^7 spores/mL), incubated in a water bath (35 °C, 125 rpm, 24–120 h).	<ul style="list-style-type: none"> • Effluents with decreased chemical oxygen demand (COD) values and protein-rich fungal biomass for feed applications may be produced from effluent water from the processing of fish. • To lower COD levels and enhance effluent water treatment, chemical measures must be used. • Fish processing companies benefit from the variety of fungus culture, which should be reinforced by research on the environment, the economy, and nutrition. 	(Sar, Ferreira, and Taherzadeh 2021)
6	Fish by-products	Solid-state fermentation	Fish by-products of shortfin scad (<i>D. macrosoma</i>)/ <i>Lactobacillus casei</i> strains (LC216, LC217, LC219, LC220 and LC221)	Mixed fish by-products with sterilized distilled water (in conical centrifuge tube), inoculated starter culture 5% (v/v) (10^7 – 10^8 CFU/mL), Sampled every 12 h and centrifuged ($10,000 \times g$, 20 °C for 10 min).	<p>Fish protein hydrolysates produced using <i>L. casei</i> strains have higher antioxidant activity (82.8–88.4%) than unfermented fish by-products (78.9%).</p> <p>Fish protein hydrolysates have much lower half-maximal effective concentrations than unfermented fish by-products.</p> <p>The ferrous chelating capacity of fish protein hydrolysates made with strain LC217 was increased by 68.43%.</p> <p>The maximal growth inhibition against harmful bacteria was substantially greater in the fish by-products produced with strains LC216 and LC217.</p>	(Abd Rashid et al. 2022)
7	Crab processing side streams	Solid-state fermentation	Brown crab processing side streams/ <i>Pseudoalteromonas Carrageenovora</i> DSM 6820 ^T , <i>Psa. rubra</i> DSM 6842 ^T , <i>Psa. tunicata</i> DSM 14096 ^T , <i>Psa. arctica</i> DSM 18437 ^T , <i>Psa. issachenkonii</i> LMG 19697 ^T	Placed crab processing side streams in sterile Erlenmeyer flasks, added sterilized solution (2% (w/v) of NaCl, 0.1% (v/v) of acetic acid), inoculated 10% (v/w) (10^7 CFU/mL), fermented (21 or 25 °C (determined by bacteria type), 72 h, 140 rpm), heated in a water bath (98 °C, 10 min). Control: Fermentation without added inoculum.	<ul style="list-style-type: none"> • <i>Psa. issachenkonii</i> obtained the maximum hydrolysis level of 14.92% after 72 h. • The hydrolysates of <i>Psa. rubra</i> and <i>Psa. tunicata</i> had the highest 2,2-diphenyl-1-picrylhydrazyl and 2,2'-azino-bis radical scavenging capabilities, respectively. • Anthelmintic activity of <i>Psa. issachenkonii</i>, <i>Psa. arctica</i>, and <i>Psa. rubra</i> showed 99% mortality rate. • At 500 g/mL, <i>Psa. arctica</i> and <i>Psa. issachenkonii</i> hydrolysates may dramatically decrease <i>Staphylococcus epidermidis</i> RP62A biofilm development. • Marine <i>Pseudoalteromonas</i> bacteria fermentation can be used to produce bioactive compounds from brown crab processing side streams. 	(Sar, Ferreira, and Taherzadeh 2021)



Table 2. Continued.

	Type of side stream	Fermentation method used	Substrate/organism	Fermentation conditions	Observations	Reference
8	Shrimp head side streams	Solid-state fermentation	Shrimp (<i>Pandalus borealis</i>) heads/ <i>Bacillus licheniformis</i> OPL-007	Inoculated autolyzed shrimp heads (natural pH, 50 °C, 4h) by activated <i>B. licheniformis</i> (10%, 30%, 50%, 70%, and 90%), fermentation temperature (30 °C, 37 °C, 40 °C, 50 °C, and 60 °C), fermentation time (0, 2, 4, 6, 8, and 10 h).	<ul style="list-style-type: none"> An effective approach to deproteinizing shrimp heads with lower energy consumption and increased capacity involved fermentation using <i>Bacillus licheniformis</i> in conjunction with autolysis. Protein powder made from the fermentation broth was high in trace elements and amino acids. This study demonstrated a cost-effective and environmentally acceptable bioprocess for using shrimp heads, which may be used as an alternate technique to harvest crustacean resources 	(Guo et al. 2019)
9	Shrimp side streams	Solid-state fermentation	Shrimp head and shell/ <i>Bacillus licheniformis</i>	Mixed distilled water and shrimp side streams, grown <i>B. licheniformis</i> (Luria-Bertani medium, 1% (v/v) (seed solution), inoculated (5% (v/v)), cultured (30 °C, 48 h), incubated (50 °C, 5 h), added seed solution to shrimp side streams (1:1), and cultured (50 °C, 6 h).	<ul style="list-style-type: none"> According to the findings, several types of shrimp side streams are excellent sources of chitin, protein, and elemental calcium extraction. The fermentation-organic process produced chitin that was as pure as that obtained using chemical means. The thermal stability, acetylation rate, and crystallinity index were lower for fermentation-organic chitin. When chitin is extracted, protein and calcium may be recycled to create high-quality raw materials. 	(Zhou et al. 2021)
10	Fish side streams and discard fish	Solid-state fermentation	Fish side streams and discard fish/ <i>Enterococcus gallinarum</i> , <i>Pediococcus acidilactici</i> , <i>Streptococcus</i> spp., <i>Lactobacillus plantarum</i> , and <i>Lactobacillus brevis</i>	Minced fish, divided into six equal groups, inoculated groups with 5% (10 ⁸ CFU/mL), added potassium sorbate, 15% molasses, and butylated hydroxytoluene, stored all groups (27 °C, stirred until ripening (daily)). Control: Using with 3% formic acid (FA, v/w).	<p>Compared to silages made with <i>Equulites klunzingeri</i>, <i>Carassius gibelio</i> silages ripened faster.</p> <p>The non-protein nitrogen value in all silage groups increased somewhat (0.4–0.7g/100g).</p> <p>Formic acid groups had higher thiobarbituric acid reactive substance values than fermented groups.</p> <p>The maximum lipid stability was found in fish silages made with <i>L. brevis</i> and <i>Streptococcus</i> spp.</p> <p>Starting cultures of lactic acid bacteria may be utilized to make high-quality animal feed from leftover fish.</p>	(Ozyurt et al. 2020)
11	Fish scales	Solid-state fermentation	Five types of fish scales (<i>Cirrhinus mrigala</i> , <i>Cyprinus carpio</i> , <i>Mugil cephalus</i> , <i>Catla catla</i> , and <i>Labeo rohita</i>)/ <i>Bacillus altitudinis</i> GVC11	Assay various concentrations of fish scales in conical flasks (0.5–2.5%), inoculated <i>B. altitudinis</i> with 2% (v/v) (10 ⁸ CFU/mL), incubated (37 °C, 200 rpm).	<ul style="list-style-type: none"> <i>B. altitudinis</i> GVC11 produced maximum alkaline protease using these fish scales. Protein hydrolysate, which may be utilized as organic fertilizer and animal feed, was enhanced with necessary and non-essential amino acids. Fish scales provide a substrate for the synthesis of alkaline proteases, which lowers expenses. Substrate use of fish scales reduces side streams concentration and environmental pollution. 	(Harikrishna et al. 2017)

inflammatory disease as well as autoimmune diseases. (Kim and Mendis 2006). Over the recent years, the economic worth of fish oil has seen a decline, primarily attributed to issues related to irregularities in demand and supply. Projections suggest that this trend is likely to persist in the foreseeable future (Turchini, Torstensen, and Ng 2009). There is a growing imperative to swiftly adopt and identify viable alternatives to fish oil to address the challenges posed by the escalating demand. Consequently, there is a heightened focus on exploring supplementary sources of fish oil. In fish industry lipids regained from fish industry side stream can be used to as an excellent replacement to fish oil as well as meet the demand for fish oil to a certain extent. Biological method like fermentation is gaining importance in this context. Fermentation is considered as microorganisms' growth in food waste enable bioconversion which provide safe as well as effective release of components from food matrices (S. F. Bruno et al. 2019; Dessie et al. 2020; Shavandi et al. 2019). Lactic acid bacteria (LAB) dependent bioconversions have the advantage that it makes inedible fish edible, fewer toxicity, conserve and reduce cooking time and nutrition. LAB fermentation enables breakdown of sugars to lactic acid which cause pH to lower 3.5, as a result due to low pH. Lipases behave as triacylglycerol hydrolases which can also catalyze the production of ester complexes. Fish viscera are a good source of 19 to 21 lipids. Lipids up to 85% can be recovered by fermentation (Rai et al. 2010).

In fish industry waste, lipid content is reported to be in between 4 and 43.8%. These lipids are a considerable source of polyunsaturated fatty acids (PUFA) which are susceptible to oxidation. Fish visceral waste and peroxide value is seen to increase up to three to four days of fermentation during autolysis of fish visceral waste. Fish oil recovery conventional method involves physical treatments such as heating as well as separate oil by centrifugation. From fish visceral waste, solvent can be employed for removal of oil which is not a cost-effective approach. Reclamation of oil from fish visceral side stream can be studied using lactic acid fermentation (Rai et al. 2011). During fermentation the quality of oil recovered shows that lactic acid fermentation (LAF) is considered as a better methodology for regaining of oil with less effect on quality. The fatty acid composition of oil recovered through fermentation is indistinguishable from that obtained through solvent extraction. In terms of fatty acid composition, there is an even distribution of both saturated and unsaturated fatty acids (Rai et al. 2011). In case of fish processing side stream, oil recovered can be a competent alternative sources of fish oils which are rich in unsaturated fatty acids.

In comparison to meat, lipids extracted from the viscera and head of both freshwater and marine fishes exhibit higher levels (Rai et al. 2011; Swapna et al. 2010). A promising substitute for fish oil lies in the fatty acid composition derived from these fish-derived lipids. These lipids, along with carotenoids, offer diverse bio functionalities. Microorganisms play a crucial role in the fermentation process, including aerobic, anaerobic, or facultative bacteria, fungi, mycelium, or microalgae. These all enable production of hydrolytic enzymes which include lipase, chitinase and proteases. which depends on microorganisms involved in the replacement of alkali during conventional treatment for proteolysis which help in demineralization and deproteination of waste. Lactic acid bacteria help in bioconversion, helps in nutrition enhancement which makes inedible food edible, preserve, and decrease cooking time, less toxic. LAB fermentation helps breakdown of sugar to lactic acid which result in low PH as 3.5. The low PH helps in optimal activity of enzymes such as acid proteases which will release protein bound to carbohydrates, lipids, carotenoids, and minerals in the waste. The acid will react with the calcium carbonate which is the main mineral component which form calcium lactate which result in control growth of the contaminant microorganisms as well as the demineralization of cells. Microbial fermentation is favored for its simplicity, rapidity, easy handling, and controllability, with minimal organic solvent requirements. It offers safety, low energy consumption, and environmental friendliness. Chitin bio-extraction, a cleaner, green, economical process, benefits from fermentation, enhancing the quality of protein hydrolysates, chitin, and oil, while producing antioxidants (Marti-Quijal et al. 2020). Lactic acid fermentation (LAF) has been employed for chitin production since the 2000s, and fish viscera fermentation can recover lipids, constituting 19% to 21% of the content (Rai et al. 2010). Table 3 depicts the major fermentation technologies adopted for the recovery of lipids from seafood side streams.

Extraction of bioactive peptides from seafood side streams using fermentation method

Fermentation is a very well accepted process to produce bioactive peptides (BPs) from organic substrates imparting chemical changes through action of enzymes produced by microorganism. Fermentation process on the basis of use of water can be divided in to two types such as solid-state fermentation (SSF) and submerged fermentation (SmF). In the SSF process, microorganisms are allowed to grow on organic materials/solid surface with no free water availability for the product formation. However, in SmF, microorganisms are cultured in a water rich nutrient medium where the

Table 3. Fermentation technologies for recovery of lipid from seafood side streams.

Type of side stream	Fermentation method used	Substrate/organism	Fermentation conditions	Reference
Tuna waste	Lactic acid fermentation	<i>Staphylococcus epidermidis</i>	pH-7, 55°C	Esakkiraj et al. (2010)
Fresh water viscera	Lactic acid fermentation	<i>Pediococcus acidilactici</i>	37°C	Rai et al. (2010)
Cod by-products	Lactic acid fermentation	<i>Enterococcus faecium</i>	37°C	Dumay, Bartheleuf, and Berge (2004)
Fresh water fish head	Lactic acid fermentation	<i>Pediococcus acidilactici</i>	37°C	Rai et al. (2011)
Fresh water fish head	Lactic acid fermentation	<i>Enterococcus faecium</i>	37°C	Rai et al. (2011)

substrate is consumed rapidly, and the BPs are synthesized and secreted to the culture medium. Depending upon the nature of the microorganism used, there are anaerobic, continuous, or fed batch fermentation processes (Mauerhofer et al. 2019). Fish processing industry waste is one of the important organic substrates of high protein content used for production BPs through all these fermentation processes (Abu Yazid et al. 2017; Chandrasekharan 2015; Mohapatra et al. 2017; Rashid, Jung, and Kim 2018). The complex protein molecules are broken down by the action of proteolytic enzymes produced by the microorganisms to short amino acid sequences of 2 to 20 residues. These are low molecular-weight compounds of less than 6,000 Da and often possess N-terminal and C-terminal amino acid residues (Saadi et al. 2015). These short chain amino acids, for their structural features exhibit functional characteristics as BPs (Chaudhary et al. 2021). The BPs are known for their anti-oxidative, antidiabetic, antimicrobial, antihypertensive, anti-cancer and immunomodulatory properties (Kang et al. 2019; Najafian and Babji 2012; Ngo et al. 2016; Nirmal et al. 2022; Phadke et al. 2021; Yaghoubzadeh et al. 2020) is represented in Table 4. Fermentation process employs different microorganism such as yeast, fungus and bacteria for the degradation of complex biomaterials. The lactic acid bacteria (LAB) are very commonly used for the fermentation of fish waste (Venugopal and Sasidharan 2022). The LAB, Gram positive bacilli are the eco-friendly microbes generally regarded as safe (GRAS) especially used for fermentation of fish processing waste.

Fermentation and antioxidant peptides

Lactobacillus, utilizing cell envelope proteinases (CEP), hydrolyzes proteins bound with various nutrients in seafood side streams, releasing peptides and free amino acids into the fermentation media (Savijoki, Ingmer, and Varmanen 2006). The resulting lactic acid production reduces media pH, controlling contaminant microorganism proliferation. In a study by Ruthu et al. (2014), three LAB strains isolated from fish waste were evaluated for fermenting freshwater fish head waste. Conditions included 10% (w/w) glucose, 2% (w/w) NaCl, and 10% (v/w) LAB cultures at 37°C. *P. acidilactici* NCIM5368 exhibited a significantly lower degree of hydrolysis compared to the other groups, all of which showed similar degrees of hydrolysis. The hydrolysates from all three groups demonstrated good antioxidant activity, confirmed through total antioxidant activity (TAO) and DPPH radical scavenging activity analysis. The LAB fermentation is also considered as the cost-effective method for fish waste valorization and production of BPs. A study conducted by Rajendran et al. (2018) demonstrated that fermentation of fish waste taking mixture of two strains of LAB such as *Lactobacillus plantarum* CNCM MA 18/5U (>1.3 × 10¹⁰ cfu/g), and *Pediococcus acidilactici* CNCM MA 18/5M (>1.3 × 10¹⁰ cfu/g) in a media of deproteinized whey 5% (wt/wt) had a clear edge over enzymatic and intentional acidification for production of antioxidant peptides. However, the authors reported that the generation of antioxidant peptides from fish waste were because of inherent proteases in the tissues of the

fish residue and was not of LAB origin. The fermentation of sea bass by-products (skin, head, tail, thorns, and backbone) with lactic acid bacteria (LAB) isolated from the three regions of the digestive system (stomach, small intestine, and colon) resulted in the production of DL-3-phenyl-lactic acid and benzoic acid (MartiQuijal, Remize, et al. 2020). They obtained the best antioxidant activity in the extracts of fermented fish by-products broth by bacteria isolated from the colon (6502 μM TE) and stomach (4797 μM TE). Fish sauce is a fermented fish product and very popular in Southeast Asian countries. The fish sauce by-product (FSB) is discarded after collection of high value fish sauce. A study conducted by Choksawangkarn et al. (2018) found that FSB is a good source of protein and bio-active compounds especially antioxidant peptides. The crude protein content was 10% in FSB and quality of protein in fish sauce and FSB were the same. The FSB was rich in tyrosine confirmed through paper chromatographic studies. The anti-oxidation property in FSB could be due to the presence of tyrosine. Because the phenolic side chains found in the structure of tyrosine is a free radical scavenger and stops the continuous reaction of radicals (Lassoued et al. 2015). The DPPH radical scavenging assay also revealed the presence of low molecular weight antioxidant molecules in the FSB extract which were identified as PQLLLLLL and LLLLLLL peptide. These extracted molecules could be used as functional ingredients in other food/feed products. Japanese fish miso, made by fermenting fish paste with *A. oryzae*-inoculated koji, is a rich source of antioxidants. Giri, Nasu, and Ohshima (2012) assessed the antioxidant activity of matured fish miso using a linoleic acid oxidation model, attributing radical-scavenging activity and linoleic acid oxidation inhibition to antioxidative peptides (<500 Da) formed during fermentation. The study concluded that various discarded fish types can be fermented with *A. oryzae* to create functional fish miso. Fang et al. (2017) found that fermenting discarded turbot skin with *Saccharomyces cerevisiae*, *A. oryzae*, and *Streptococcus thermophilus*, with *A. oryzae* yielding the highest skin protein hydrolysis. *A. oryzae*'s potential for fermentation lies in its multiple protease-coding genes, enhancing protein component hydrolysis (Vishwanatha, Rao, and Singh 2009). The fermented hydrolysates exhibited DPPH inhibitory activity, with *A. oryzae* fermented hydrolysate displaying the highest antioxidant activity due to its unique amino acid profile. Lactic acid fermentation of shrimp waste using innovative substrates like whey and molasses yields proteins, lipids, and carotenoids in the fermentation liquor (Cabanillas-Bojórquez et al. 2021). The antioxidant activity of the liquor, attributed to carotenoids, measures 54.43 ± 4.73 μM Trolox equivalent/g via the ABTS method. Shrimp waste's principal carotenoid, astaxanthin, demonstrates remarkable antioxidant potency, surpassing β-carotene by 10-fold and vitamin E by over 500 times (Afonso et al. 2016; Higuera-Ciapara, Felix-Valenzuela, and Goycoolea 2006). Shrimp fermentation waste shows promise for feed and pharmaceutical applications. Cabanillas-Bojórquez et al. (2021) optimized supercritical CO₂ conditions for astaxanthin extraction from lactic acid-fermented shrimp waste, extracting 0.6353 μg/g astaxanthin under 300 bar pressure, 60°C

Table 4. Fermentation process for recovery of bioactive peptides from seafood side streams.

Fermentation/enzymatic hydrolysis	Type of peptides	Type of side stream	Substrate/organism m/enzymes	Fermentation conditions/preparation of hydrolysate	Bioactive peptide component	Activity characteristics	Reference
Fermentation	Antioxidant	Freshwater fish (catla and rohu) head waste	<i>Pediococcus acidilactici</i> NCIM5368, <i>Enterococcus faecium</i> NCIM5335 and <i>Pediococcus acidilactici</i> FD3	10 % (w/w) glucose, 2 % (w/w) NaCl and 10 % (v/w) LAB cultures at 37°C.	Hydrolysate	Good total antioxidant activity (TAO), and DPPH radical scavenging activity	Ruthu et al. (2014)
		Sea bass by-products (skin, head, tail, thorns, and backbone)	Lactic acid bacteria (LAB) isolated from the three regions of the digestive system (stomach, small intestine, and colon		DL-3-phenyl-lactic acid and benzoic acid	Best antioxidant activity	Martí-Quijal et al. (2020)
		Fish sauce by-product (FSB)			PQLLLLLL and LLLLLL	First grade FSB had stronger DPPH and hydroxyl radical scavenging activity and reducing ability	Khositanon et al. (2018)
		Fermented anchovy fish sauce			Antioxidant peptides, Lue-Asp-Asp-Pro-Val-Phe-Ile-His (LDDPVFIH) and Val-Ala-Ala-Gly-Arg-Thr-Asp-Ala-Gly-Val-His (AAGRTDAGVH)	Higher antioxidant activity	Najafian and Babji (2019)
		Discarded turbot skin	<i>Aspergillus oryzae</i>			Highest hydrolysis of skin protein	Fang et al. (2017)
		Shrimp waste	Lactic acid fermentation	300 bar pressure, 60°C temperature, and 6 mL/min flow rate of supercritical CO ₂ , 0.6353 µg/g	Astaxanthin from lyophilized liquor	Antioxidant activity against different free radicals and can be utilized in food supplements	Cabanillas-Bojórquez et al. (2021)
		Speckled shrimp by-product	<i>Anoxybacillus kamchatkensis</i> MTVa	In a shrimp media powder at 25 g/L	Hydrolysate	High level of protease activity rich source of antioxidant with enzymes inhibitory potential	Mechri et al. (2020)
		Fish waste	<i>Yarrowia lipolytica</i>		Hydrolysate	Strongest antioxidant activity (86.4% in DPPH assay) and volatile compounds	Gottardi et al. (2022)
Antimicrobial		Fish processing wastes	<i>Pediococcus acidilactici</i> NCIM5368, <i>Enterococcus faecium</i> NCIM5335 and <i>Pediococcus acidilactici</i> FD3		Hydrolysate	Good antibacterial activity. Antifungal activity	Ruthu et al. (2014)
		Milkfish obtained from fish bone, scales and skins. Fish skin.	<i>Bacillus licheniformis</i> and <i>Bacillus thuringiensis</i> <i>Bacillus cereus</i> FORC005 and <i>Bacillus cereus</i> FRCY9-2	Alkaline condition at 55°C for 30 to 60min	Collagen Collagen	Antifungal properties against <i>Candida albicans</i>	Kusumaningtyas, Nurilmala, and Sibarani (2019) R. Ahmed et al. (2018)

temperature, and 6 mL/min flow rate. The extracted liquor exhibits antioxidant activity against various free radicals, suitable for food supplements. Shrimp by-products, rich in bioactive compounds, can be employed in food, feed, pharmaceutical, textile, and agricultural industries, challenging the perception of these by-products as "waste" (Seedevi et al. 2017). Bioprocessing shrimp by-products with proteolytic microorganisms is gaining traction, producing metabolites with high bioactivity potential (Mechri et al. 2019). Proper drying of fermented shrimp processing by-products preserves their functional properties, making them valuable in feed applications (Ghorbel-Bellaaj et al. 2018).

Fermentation and antimicrobial peptides

Antimicrobial peptides (AMPs) are very diverse group of molecules. It is less than 10 KDa weight with average 33.19 amino acid residues (Baco et al. 2022; S. Wang et al. 2016). The AMPs are part of the innate immune defense system and protects the host from broad range of microorganisms, including bacteria, fungi, parasites and viruses (Das, Pradhan, and Pillai 2022; Mohammed, Said, and Dua 2017). AMPs exhibit amphipathic conformation as both hydrophobic and hydrophilic groups attached with it (L. T. Nguyen, Haney, and Vogel 2011). These peptides neutralize the pathogenic microbes by blocking membrane ion gradients, interacting with the cytoplasmic membrane, forming pores and even altering cell metabolism (Hoelscher et al. 2022; Q. Y. Zhang et al. 2021). The antimicrobial peptides are also known for their inhibition activity to Gram-positive and Gram-negative bacteria (Huan et al. 2020).

The anti-microbial resistance of microorganisms is a serious concern due to rampant use of antibiotics in agriculture and animal husbandry sectors worldwide (Manyi-Loh, et al. 2018). There is an urgent need of antibiotic alternatives. Antimicrobial peptides are suitable alternatives to antibiotics as they are effective against multi drug resistance pathogens (Rima et al. 2021). Several antibacterial peptides have been derived and reported from sea foods and sea food side streams. Enzymatic hydrolysis is one of the commonly adopted processes to derive bioactive peptides from the sea food by-products. The common enzymes which are used for this purpose are pronase, bromelain, protease A and N, orientase, neutrase, protamex, validase, pancreatin, alcalase, trypsin, papain, pancreatin, and thermolysin and flavourzyme (Abuine, Rathnayake, and Byun 2019; Lorenzo et al. 2019). However, fermentation employing microbes is also suitable for the production of AMPs. Among microbes, *Bacillus* species and *Aspergillus* spp. are proficient in production of enzymes suitable for the fermentation of sea food side stream and production of AMPs. Ruthu et al. (2014) fermented fish waste with three strains *Bacillus* (*Pediococcus acidilactici* NCIM5368, *Enterococcus faecium* NCIM5335 and *Pediococcus acidilactici* FD3) isolated from fish processing wastes the obtained hydrolysate exhibited good antibacterial activity and it was ascertained through checking against a number of Gram-positive and Gram-negative microbes. The fermented hydrolysate from all three groups also showed

antifungal activity. The extract fermentation with *E. faecium* NCIM5335 was found to be efficient and effective compared to *P. acidilactici* FD3 and *P. acidilactici* NCIM5368 against *Penicillium* compared to *A. oryzae* and *A. ochareus*. This work is one of the few reports of LAB fermentation produced both antibacterial (bacteriocin) and antifungal peptides from fish waste.

Fish side streams, including skin, scale, and bone, are rich sources of valuable products such as collagen and peptone. Collagen extraction methods include using collagenolytic protease (CP) bacteria, as demonstrated by R. Ahmed et al. (2018) with *Bacillus cereus* FORC005 and *Bacillus cereus* FRCY9-2, yielding higher collagen (188 g/kg waste) compared to bacteria with acid (177 g/kg) or acid extraction alone (134.5 g/kg). Enzymatic hydrolysis of collagen produces the antimicrobial peptide collagencin, which exhibits broad-spectrum antibacterial activity through a carpet mechanism. Collagen-derived peptides from fish, such as SIFIQRFTT, RKSGDPLGR, AKPDGAGSGPR, and GLPGLGPAGPK, demonstrate antibacterial properties, with GLPGLGPAGPK showing activity against both Gram-positive and Gram-negative bacteria (Ennaas et al. 2015). Peptone, another valuable product from fish waste, is widely used in microbiological media for microbial synthesis of antimicrobial peptides and metabolites. Fish-derived peptone, obtained through enzyme hydrolysis, is comparable to commercial peptone, and peptones from specific fish sources, like river pangasius catfish and magur catfish, may even be more effective for bacterial growth than commercial counterparts (Setijawati et al. 2020). Maky and Zendo hydrolyzed fish samples using pepsin enzyme, yielding a peptide effective against a wide spectrum of foodborne pathogens and spoilage bacteria.

Enzymatic hydrolysis and bioactive peptides

Solvent extraction, enzymatic hydrolysis, and microbial fermentation are key methods for extracting bioactive peptides (BPs) from marine proteins. Microbial fermentation yields silages and fish protein hydrolysates containing antioxidants and antimicrobial peptides. Lactic acid fermentation, while generating lipids, poses challenges in lipid removal from the hydrolysate, making it suitable for animal feed. In food and pharmaceutical industries, enzymatic hydrolysis is preferred for its absence of residual organic solvents or toxic chemicals (Ryan et al. 2011). Acid and alkali hydrolysis have drawbacks, as they destroy certain valuable amino acids, diminishing bioactivity potential. Acid treatment, for instance, completely destroys tryptophan and causes varying degrees of destruction to serine, threonine, asparagine, and glutamine (H. Gu et al. 2015). In contrast, enzymatic hydrolysis, conducted under controlled pH and temperature conditions, is well-suited for producing low molecular weight bioactive peptides with unique amino acid sequences. Crude hydrolysates are subsequently fractionated to separate individual peptides using different techniques, mainly reverse phase high performance liquid chromatography (RP-HPLC) or gel permeation chromatography (Ryan et al. 2011). The



bioactive peptides generate through enzymatic hydrolysis show calcium binding, antidiabetic, antihypertensive and anticancer properties and that has been described in this section.

Calcium-binding peptide

Calcium (Ca) is a very important mineral for animal as well as human nutrition. The bioavailability of Ca can be enhanced when provided along with a protein phosphopeptide complex or by simple fortification in the staple food. Fish scales are good source of protein and have strong affinity to bind with Ca. In this regard, Y. Lu et al. (2016) conducted experiment to find out Ca-binding peptide from tilapia scale protein hydrolysates on calcium absorption in Caco-2 cells. Tilapia scale protein hydrolysates were prepared by treating the scale powder with pepsin, trypsin and flavourzyme with suitable quantity and at proper pH and temperature. The isolation of Ca binding peptides was done with sephadex G-15, and the calcium uptake was estimated using Caco-2 cells in DMEM cell culture media. The Ca uptake increased by the calcium binding peptides than from CaCl_2 . The results suggest that peptide-calcium complex is a bioavailable form of Ca. The snapper fish scale protein hydrolysate-Ca complex also exhibited improved calcium cellular uptake and resisted the inhibitory effect of dietary inhibitors (Lin et al. 2020). The Ca binding peptides has been isolated from tilapia skin gelatin enzymatic hydrolysates. Bingtong, Yongliang, and Liping (2020) purified two peptides such as Tyr-Gly-Thr-Gly-Leu (YGTGL, 509.25 Da) and Leu-Val-Phe-Leu (LVFL, 490.32 Da) with strong calcium-binding capacity from the different tilapia (*Oreochromis niloticus*) skin gelatin enzymatic hydrolysates.

Antidiabetic peptide

Numerous diabetes prevention strategies such as controlling carbohydrate rich food to insulin injection are followed by the patients. Bioactive food derived peptides has also been reported to maintain the glucose homeostasis due to their capacity to inhibit the digestive enzymes. Fish derived proteins and peptides are also very effective in increasing glucose uptake and glucose tolerance, reducing blood glucose concentrations, and up-regulating GLUT4 and PPAR- α (Zhou et al. 2021). Oral administration of 300 mg/day Atlantic salmon skin gelatin hydrolysate for five weeks in streptozotocin-induced diabetic rats inhibited dipeptidyl peptidase IV (DPP-IV) activity, increased plasma glucagon-like peptide-1 (GLP-1), insulin, and the insulin-to-glucagon ratio, suggesting its potential for regulating glucose metabolism (Hsieh et al. 2015). DPP-IV, a homodimeric serine peptidase, plays a crucial role in regulating glucose metabolism by interacting with peptides like GLP-1 and deactivating their insulinotropic activity (Liu, Cheng, and Wu 2019). So, inactivation of DPP-IV is the key target for the treatment of T2DM. As per a report, halibut and tilapia skin gelatin hydrolysates inhibited in vitro DPP-IV activity (38–51%) and increased the glucose tolerance in diabetic rats through the

inhibition of plasma DPP-IV activity, increase of GLP-1 and insulin secretion when administered at a dose 750 mg/kg/day for 30 days (T. Y. Wang et al. 2015). Peptide fraction from Atlantic salmon (*Salmo salar*) frames improved the glucose tolerance and reduced the activation of TORC1/S6K1/IRS1 nutrient-sensing pathway in liver of male mice fed at a dose of 50% in the diet for 12 weeks (Chevrier et al. 2015). Decreased blood glucose level was found in mice with alloxan induced diabetes when provided with tilapia skin collagen peptides at dose of 0.85 and 1.7 g/kgbw for 25 days (R. Zhang et al. 2016). The peptides derived from *Sardine pilchardus* muscle proteins by hydrolyzing with a combination of three enzymes, such as subtilisin, trypsin and flavourzyme showed highest DPP-IV inhibitory activity with an IC₅₀ value of 1.83 mg/ml (Rivero-Pino, Espejo-Carpio, and Guadix 2020). The discarded shrimp (*Penaeus vannamei*) head was hydrolyzed with five food grade proteases. The peptides generated were identified by LC MS/MS and four potential peptides YPGE, VPW, HPLY, YATP showed $40.90 \pm 2.76 \mu\text{M}$, $174.781 \pm 5.08 \mu\text{M}$, $461.89 \pm 3.23 \mu\text{M}$, $475.33 \pm 6.24 \mu\text{M}$, IC₅₀ value, respectively (Xiang 2021). The authors concluded that discarded *P. vannamei* head is a promising natural source of DPP-IV inhibitor and can improve glycaemic control in Type 2 diabetes.

Antihypertensive peptides

According to WHO, approximately 1.28 billion adults aged 30–79 in low and middle-income countries have hypertension, necessitating various drug treatments. These include calcium channel blockers, renin-angiotensin system inhibitors, beta blockers, alpha blockers, diuretics, vasodilators, and ACE inhibitors, each with distinct mechanisms in controlling hypertension and potential side effects (Olowofela and Isah 2017). In hypertension prevention and treatment, natural products like fish-derived peptides have shown promise. These peptides, purified from seafood and side streams, are low in molecular weight (<1 kDa), with fewer than 20 amino acids, primarily consisting of arginine, valine, and leucine. Fish protein hydrolysates (FPH), prepared with food-grade enzymes, serve as good sources of ACE-I inhibitory peptides. ACE inhibitory peptides, extracted from various fish species and by-products, include those obtained from salmon pectoral fin through enzyme hydrolysis (Ahn et al. 2012). Purified ACE inhibitory peptides, such as Val-Trp-Asp-Pro-Pro-Lys-Phe-Asp (P1), Phe-Glu-Asp-Tyr-Val-Pro-Leu-Ser-Cys-Phe (P2), and Phe-Asn-Val-Pro-Leu-Tyr-Glu (P4), exhibit IC₅₀ values against ACE activity ($9.10 \mu\text{M}$, $10.77 \mu\text{M}$, and $7.72 \mu\text{M}$, respectively). These peptides have been isolated from various salmon species (Y. Gu, Majumder, and Wu 2011; Neves et al. 2017; Ono et al. 2006). ACE-inhibitory peptides have been identified in marine species like krill (Park, Je, and Ahn 2016), pacific cod (Ngo et al. 2016), sardinelle (Jemil et al. 2017), and tuna (Martínez-Alvarez et al. 2016), as well as in freshwater fishes such as tilapia (Toopcham, Roytrakul, and Yongsawatdigul 2015) and grass carp. These peptides exhibit proven ACE-I inhibitory activity and antihypertensive effects, validated through in vitro and in vivo studies. Their potential as antihypertensive drugs should be highlighted.

Anti-cancer peptides

Cancer treatment involves various complex methods, such as chemotherapy, surgery, radiation, immunotherapy, gene therapy, and nanomedicine (Arruebo et al. 2011). Due to the side effects of chemotherapy and anticancer drugs, there's a growing reliance on natural compounds with anticancer properties (S. Ahmed et al. 2021; Pangestuti and Kim 2017). Bioactive peptides from natural aquatic products can modulate molecular pathways related to DNA defense, cell-cycle control, and apoptosis initiation, making them potential candidates for cancer treatment (Kang et al. 2018). Protein hydrolysates from fish, amphibians, and turtles show potential in cancer treatment. Shark cartilage extract, particularly Neovastat (AE-941) from *Squalus acanthias*, demonstrates anti-tumor, anti-angiogenic, and anti-inflammatory properties. AE-941 disrupts the signaling pathway of vascular endothelial growth factor (VEGF) to its receptor (VEGFR), inducing apoptotic activities in endothelial cells (Gingras et al. 2003). Active oxygen species related oxidative stress can cause cancer in human being and antioxidants are potential candidates to control it (Umayaparvathi et al. 2014). The fish protein hydrolysate is a good source of antioxidant has been reported from different fish by-products (discussed earlier in this section). Halim et al. (2018) fractionated eel protein hydrolysate (EPH) which exhibited antioxidant property and anticancer activity as well. The anticancer activity was determined by 3–4, 5-dimethylthiazol-2-yl-2, 5-diphenyltetrazolium bromide (MTT) assay using MCF-7 cell lines. The antioxidant and anticancer activities of bioactive peptide isolated from oyster (*Saccostrea cucullata*) protein hydrolysate were evaluated in vitro by Umayaparvathi et al. (2014). The oyster peptide SCAP1 showed both antioxidant and anticancer activity against human colon carcinoma (HT-29) cell lines. Similarly, Yaghoubzadeh et al. (2020) reported that antioxidant and anticancer properties of rainbow trout (*Oncorhynchus mykiss*) skin protein hydrolysate prepared using Alcalase (HA) and Flavourzyme (HF) enzymes. The antioxidant characteristics of hydrolysates ascertained through DPPH radical inhibitory power and ferric reducing assay. The anticancer properties of the hydrolysates were tested in MTT assay and using HCT-116 cell line. The isolated fractions on HCT-116 cancer cells showed cytotoxic properties and inhibit the growth of these cells in vitro.

Application potential of fermented seafood side streams in animal nutrition

Fish protein hydrolysates (FPH) are obtained by chemicals acid, enzymatic hydrolysis or by microbial fermentation of by-products. The amino acid composition of FPH is well-balanced, and highly digestible in animal feed (Ananey-Obiri, Matthews, and Tahergorabi 2019; Zheng et al. 2012). Seafood protein hydrolysates contain low molecular weight compounds and molecules having the ability to stimulate the production of insulin like growth factors that are favorable for growth, feed performance, immunity and survivability of the animals. The FPH industry is witnessing a growing demand from the feed manufacturers in order to reduce the production cost of feed. The use of FPH has

potential to replace traditional protein sources such as FM and soybean meal from the diets of fish and animals (Siddik et al. 2021). The addition of FPH at appropriate concentration has been found to increase the growth rate of fish (Egerton et al. 2020), poultry bird, pig and sheep.

Application of FPH in aquafeed

The growing aquaculture practice is heavily dependent on continuous supply of good quality feed. Fishmeal (FM) is generally considered the benchmark ingredient in aquafeed formulations due to the balanced amino acid profile and other nutrients. However, due to over demand and escalating price the replacement of FM with alternative proteins is given a lot of emphasis. Fisheries and aquaculture industry generates 50% and 70% of the by-products typically consist of viscera, heads, skin, bones, and blood (Stevens et al. 2018). This inedible portion is increasingly being considered as a practical option after converting to silage, hydrolysate or even FM (low quality) to replace the use of high-quality FM (Egerton et al. 2020; Hua et al. 2019; Shao et al. 2020). Fermented fish waste has additional benefits because of the antioxidant and antimicrobial properties, making them suitable for feed applications (Ruthu et al. 2014).

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FPH derived from enzymatic hydrolysis of fish waste has proven beneficial in farmed fish, positively impacting growth, feed intake, nutrient utilization, immune response, oxidative status, and disease resistance (Siddik et al. 2021). Its incorporation improves feed palatability and attraction

Table 5. Chemical composition of FPH, FSFWS and FFWS (% as-fed basis).

Items	FPH	FSFWS	FFWS
Dry matter	94.19	21.68	
Crude protein	87.90	59.27	42.09
Ether extract	0.12	18.40	
Crude ash	5.78	19.23	
Neutral detergent fiber	0.77		
Acid detergent fiber	0.05		
Essential amino acids			
Arginine	3.83	2.19	1.80
Histidine	1.68	5.85	3.08
Isoleucine	2.79	5.05	5.00
Leucine	4.56	8.00	9.31
Lysine	5.34	9.16	9.92
Methionine	0.94	6.03	4.97
Phenylalanine	2.30	4.32	4.07
Threonine	3.24	4.97	5.12
Tryptophan	0.42	0.65	0.87
Valine	3.52	5.77	5.83
Nonessential amino acids			
Aspartic acid	7.91	10.79	9.62
Alanine	7.04	7.41	8.12
Cystine	0.47	0.69	1.03
Glutamate	12.76	14.45	13.83
Glycine	13.42	5.87	6.32
Proline	7.56	3.66	5.57
Serine	3.08	3.23	3.52
Tyrosine	1.47	1.90	2.02

Note: FPH: fish protein hydrolysate; FSFWS: fermented saltwater fish silage; FFWS: fermented freshwater fish silage (Source: Arruda et al. 2006; Vidotti, Viegas, and Carneiro 2003; N. Zhang et al. 2022).

in fish due to low molecular weight peptides (Tang et al. 2008). With a suitable nutrient profile and easy digestion, FPH is an attractive option for larval feed, especially when the digestive tract is not well developed at early developmental stages. FPH provides highly bioavailable nutrients, enhances digestive enzyme activity, protein metabolism, and intestinal health, thereby increasing larval survivability and development (Sheng et al. 2022). Reported benefits of FPH supplementation include enhanced larval survival and fry growth in various fish species, including Atlantic halibut, yellow croaker, sea bass, largemouth bass, Nile tilapia, and early post-larval Pacific white shrimp (Cai et al. 2015; Khieokhajokhet and Surapon 2020; Kwasek et al. 2021; Niu et al. 2014; Tonheim et al. 2005). Fish silage and FPH are successful alternatives to FM in various species (Arruda, Borghesi, and Oetterer 2007; Elavarasan 2019). Moderate FPH inclusion (5–10% FM replacement) enhances growth performance (Egerton et al. 2020). Even at lower levels, FPH improves diet palatability and boosts fish growth (Wei et al. 2021; Xu et al. 2016). Salmon fed with 10% partly hydrolyzed fish protein and 80% plant protein exhibit comparable growth to a 35% FM diet (Egerton et al. 2020). Tiger puffer effectively utilizes FPH with plant ingredients, regulating 4E-PP1 expression to increase muscle protein synthesis (Wei et al. 2021). Dietary FPH benefits growth in black sea bream through TOR signaling pathway up-regulation (Irm et al. 2020). Stick water hydrolysate (SWH) enhances growth, immune function, and intestinal health in rice field eel when replacing 5–15% FM (Shi et al. 2019). However, FPH incorporation (>20%) decreases growth performance in various fish species (Xu et al. 2016). Nile tilapia and Japanese flounder showed reduced growth

with over 10% APH and 16% FPH, respectively (Khieokhajokhet and Surapon 2020). Turbot fed with 20% FPH also experienced significant growth reduction (Xu et al. 2016). The excess short-chain peptides and amino acids in hydrolyzed products may saturate intestinal peptide transport mechanisms, affecting growth in fish (Ospina-Salazar et al. 2016). Shrimp, however, exhibits better FPH utilization, as shown in a six-week trial with 20% tuna head hydrolysate improving growth and survival rates in Pacific white shrimp (H. T. M. Nguyen, Pérez-Gálvez, and Bergé 2012).

FPH supplementation in the diet of fish influences other biochemical responses such as hematological and immunological parameters. In red sea bream, fish fed diets containing roughly 4–5% of hydrolysates from whole Antarctic krill, white shrimp, or tilapia had considerably higher survival rates and total immunoglobulin levels than fish fed diets without these ingredients (Bui, et al. 2014). Additionally, they discovered that adding krill or tilapia hydrolysate to fish diets enhanced their resistance to *Edwardsiella tarda*. The availability of antimicrobial, anti-inflammatory, and antioxidant peptides in fish protein hydrolysates prepared with application of enzymes or through fermentation from side streams have been reported in several studies (Baco et al. 2022; Da Rocha et al. 2018). It is obvious that when these hydrolysates are provided as dietary components enhances health condition of fish. Additionally, Goosen, de Wet, and Görgens (2014) observed that phagocytic activity of hemocytes increased by 18% in comparison to the control diet when low quantities of commercial fish protein hydrolysate (Actipal, 0.6%) were added to abalone diets. A study on red seabream, *Pagrus major*, found that replacing fishmeal (FM) with fish protein hydrolysate (FPH) increased hematocrit, hemoglobin, total protein, and cholesterol levels, while decreasing plasma glucose and triglyceride levels. This suggests that dietary FPH inclusion enhances protein absorption and overall fish health (Khosravi et al. 2015). Murrel (*Channa striata*) fingerlings fed with 10% FPH showed improved serum lysozyme and myeloperoxidase, along with up-regulation of IGF-I, enhancing growth performance and immune response (Siddaiah et al. 2022). Similarly, juvenile largemouth bass (*Micropterus salmoides*) fed with 30 g/kg dry matter of FPH replacing FM demonstrated no negative effects on growth and feed utilization, and FPH supplements improved intestinal immune mechanisms to address immunodeficiency caused by FM replacement (Fan et al. 2022).

Application of FPH in pig feed

FM and soybean meal (SBM) are the conventional protein ingredients in pig feeds owing to their balance of amino acids and other nutrients. These two ingredients are relatively expensive in comparison to other protein ingredients. The presence of antinutritional factors in SBM also affects health of weaning pig (Koeppke et al. 2017). The replacement of FM with fish silage meal (FSM) has been successfully tried in pig diets. Thi Thuy, Lindberg, and Ogle (2011) fed pigs with ensiled Tra catfish (*Pangasius hypophthalmus*)

by-products (ECM) and found improved performance and meat quality of finishing pigs. However, feed intake was slightly affected due to ECM inclusion and the backfat thickness increased. The authors concluded that palatability difference due to the presence of FSM could be the reason for less feed intake with ECM and keeping the cost of production in view replacement of FM with FSM would still be profitable. Candido et al. reported that FSM, obtained from the mixture (1:1) of fish silage with corn, showed a quadratic effect on average daily gain, and the best result was obtained with the inclusion level of 25.83%. The results for feed conversion and economic viability indicate that up to 25% FSM, corresponding to 5.87% of fish silage based on dry matter, can be used in the pig growing and finishing phases. FPH is an emerging raw material in animal feed (Opheim et al. 2016). Weaning pigs' fed with salmon protein hydrolysate (SPH) and FM resulted in 12–14% increased feed consumption than those containing soy protein concentrate. However, the higher feed intake did not change weight gain and feed utilization significantly among treatments. The higher feed intake due to addition of FPH could be due to the presence of flavor-like peptides in FPH which is often released in the hydrolysis process (B. J. Bruno, Miller, and Lim 2013). Similarly, Tucker et al. (2011), observed that supplementation of up to 3% of salmon protein hydrolysate in diets does not affect the growth performance of weaning pigs. Furthermore, Opheim et al. reported that piglets fed with SPH in a weaning condition showed larger duodenal villi absorption area in comparison to the groups received plant and soy proteins. The authors also observed differences in intestinal microbiota community but no differences in growth performance between the experimental diets. The FPH hydrolysate is well accepted in pig and capable of replacement of SBM or FM but do not contribute to growth performance in general. N. Zhang et al. (2022) found that addition of 5% FPH increased the average daily feed intake (ADFI), activities of total antioxidant capacity (T-AOC), superoxide dismutase (SOD), glutathione peroxidase (GSH-Px), and immunoglobulin A (IgA). FPH in diet also resulted in high value of digestible energy and ileal digestible essential amino acids, improved nutrient digestibility, immunity, and intestinal health of piglets. But the piglets showed adverse nitrogen deposition could be the cause of decreased average daily gain (ADG) of piglets which was also obtained in the result. Contrastingly, when whole fish hydrolysate was fed replacing 75% and 100% FM significantly increased the ADG of piglets by 2.50% and 3.76% (Thuy, Joseph, and Ha 2016). This indicates FPH prepared from whole fish is superior to the FPH prepared from the side streams. The advantage of dietary fermented FM has also been noticed in weanling pigs. Addition of fermented FM to weanling pig diets increased average feed intake, final body weight, average daily gain, and gain: feed ratio improved blood hematocrit, monocyte, immunoglobulin G, and blood urea nitrogen levels. During the experimental period, diets with 0.2% and 0.5% fermented FM showed a reduction in *Salmonella enterica* and *Escherichia coli* populations which was also an indication of better gut health (H. J. Lee et al. 2017). Pigs, especially pregnant sows, are very

sensitive to a lack of protein and good combinations of essential amino acids are very essential for their health. The fermented fish processing waste as a valuable nutrient source was tried in sows feeding by Nikulin, Nikulina, and Tsoy (2021). They found that fermented fish paste based diet (fermentation process not mentioned) at a dose of 3 and 6.2% in feeding sows had a positive effect on their reproductive qualities, which allowed to increase the multiplicity of sows' livestock by 3.8–9.7%, large-scale fertility by 1.7–5%, the average daily growth of piglets by 5.4–7.8%, and increase the safety of new born piglets by 2.2–4.4%. The results related to use of FPH, levels of incorporation of FPH and fermented fish waste in pig performance is inconsistent which requires more systematic studies and approaches.

Application of FPH in broiler/other bird feed

Fishmeal is an excellent source of nutrient in poultry feed and the inclusion is still recommended at 2–10% in poultry diets (IFFO). The increasing cost of FM and presence of trimethylamine in fish meal which creates a residual fish smell and flavor in meat and eggs are the reasons of FM replacement from poultry diet (Leeson and Summers 2009). The use of fish silage as low-cost alternative to FM has also been studied in poultry diets (Johnson et al. 1985). However, replacement of soybean meal (SBM) with fermented fish waste and other plant ingredients are more recent trend. There is a huge reliance on soybean meal by poultry feed. The cost of soybean meal has increased manifold in recent years (The Economic Times). SBM, after fishmeal, is the most expensive ingredient in animal and aquafeed. The incorporation of fermented ingredients in broiler feed positively influences the gut health and production parameters (R. Zhang et al. 2016). Generally, the fermented feed contains high number of lactic acid bacteria (LAB), a low pH and a high concentration of organic acids (Canibe and Jensen 2012) which is beneficial in terms of protecting the feed from pathogen contamination, gut health, growth and development of birds (Missotten et al. 2013; Niba et al. 2009; Xie et al. 2016). In broiler chickens, replacing a part of SBM with fermented fish waste in the diet ensure improved growth performance and carcass characteristics (Shabani et al. 2016). Fish silage is a good source of highly available amino acids which helps for better growth and feed efficiency in young growing chickens (Panda et al. 2017). Enhanced growth performance, protein, and ether extract digestibility; increased activity of digestive enzymes and cecal beneficial bacteria populations; enhanced cecal short chain fatty acids (SCFA) contents (especially lactic acid and butyrate) and reduced excreta ammonia emission and cecal pathogenic bacteria populations in broiler chicks were reported by Shabani et al. (2019) feeding fermented fish waste silage as a substitute of SBM. Similar observation was also reported by Shabani et al. (2018) and Al-Marzooqi et al. (2010), sardine fish silage replaced SBM with improved performance of broiler chickens and stated that sardine fish silage had a higher digestibility coefficient of amino acids relative to SBM. Similarly, various experiments have shown that fermented products could improve broiler performance

(Ashayerizadeh et al. 2017; Chiang et al. 2009; Jazi et al. 2017; H. Sun et al. 2013). Lohmen brown chicken fed with 6% formic acid fermented fish silage adding into a commercial feed increased early egg laying, feed intake, body weight gain, egg production and average white eggs (Abelti 2018). Similarly, Opheim et al. (2016) found that addition of SPH (salmon protein hydrolysate) 5 and 10% in the starter diet increased broiler chicken growth performance compared with either a plant protein-based diet or a FM diet. The inclusion of SPH in broiler chicken starter diet increased the villi height in the duodenum and ileum in comparison to plant protein diet. The early development of small intestine is an advantage for nutrient absorption thus growth performance at older ages of broiler birds (Wijtten et al. 2010). A study conducted by Biotai et al. found that broiler chicken fed with acid treated fish silage up to 10% did not show body weight gain. However, during starter phase, the birds exhibited improved feed conversion (FC) due to the incorporation of fish silage at both 5 and 10% however; no change in FCR was recorded in later growth stages. Ambarwati and Syah (2022) evaluated the effect of dietary supplementation of flying fish silage on egg quality and duck performance. The results showed that 10% addition of flying fish silage to duck basal feed did not decrease egg quality and duck performance. The authors anticipated by increasing fish silage incorporation could increase egg quality and duck performance. The higher fish silage inclusion level was tried by Taufikrrahman et al. in duck ration and found that fermented fish waste can be used up to 20% without negative effects on interior quality of egg. A study was conducted by Tanuja et al. (2017) by supplementing acid ensiled fish waste on production performance, egg quality and serum biochemistry in layer Japanese quail (*Coturnix japonica*). Acid ensiled silage was prepared from visceral waste (gut and gills) of freshwater fishes using 1.5% formic acid (v/w) and 1.5% hydrochloric acid (HCl). The results shows that acid ensiled fish waste could be used as a protein supplement in diet of layer Japanese quail birds up to a level of 12% without affecting their production performance and quality of eggs. Lipids that are recovered from the fish processing by products by lactic acid fermentation can be an alternative to vegetable oil and commercial fish oil and can be utilized as a feed component without compromising the growth performance and meat quality of broilers (Muhammad et al. 2015).

Ruminants

Fishmeal is not considered a major source of nutrient in the feed of ruminants. Inclusion level of FM in terrestrial livestock diets is usually remains below 5% on a dry matter basis (Cho and Kim 2011). However, the supplementation of FM has benefits in terms of improved milk yield and quality (Atwal and Erfle 1992; Koushki et al. 2019), fertility (Staples and Funge-Smith 2005), enhanced ruminal fermentation (Allison and Garnsworthy 2002), faster growth (Atti, Mahouachi, and Rouissi 2007), and meat enrichment (Mandell et al. 1997). The dietary protein in ruminants is degraded in to amino acids and ammonia and by ruminal

microorganism then it is converted in to microbial protein (MCP) (Z. Lu et al. 2019). The higher MCP synthesis facilitates animal performance, reduces the protein waste and increases milk production. The protein which by passes the ruminal digestion or undegradable protein (UDP) reaches the intestine unmodified and digested by enzymatic hydrolysis. The UDP provides a direct source of amino acids for growth and metabolism of the ruminants. A lot of energy is saved in this process otherwise microbes need sufficient energy to synthesize MCP (Hackmann and Firkins 2015). Fish hydrolysate is a very good protein source but unlike FM it is easily degraded in the rumen as it is partially hydrolyzed and rich in peptides. The amino acids and peptides from the fish hydrolysate help the fibrolytic bacteria to grow and can better utilize fiber fractions in the diet. Ouellet et al. (1997) compared the effect of supplementing grass silage with FM and FPH on growth, diet digestibility and rumen fermentation in beef cattle. The FM fed group showed 25% increased daily gains in comparison 11% with FPH. This suggests that the protein from the hydrolysate is wasted in the rumen due to high solubility. However, sheep fed with *Lactobacillus plantarum* fermented fish waste showed a net increase in weight in comparison to control diet (40% barley and 60% wheat bran) and enhancement of meat characteristics and carcass shape Rahmi et al. 2008). Dietary FM increased milk production with health fatty acids in cow was observed by Atwal and Erfle, (1992). Cows fed with 1, 2, and 3% FM in their diet did not show more milk production, fat percentage and fat content of milk also were not affected by the diet composition. However, significant difference was observed than the control diet (Yazdani 2011). This is understood that when FM is utilized in cattle feed then fish silage or FPH hydrolysate could potentially be utilized for cattle performance.

Conclusion

The application of fermentation technology as a biorefining tool for recovering valuable nutrients from seafood side streams is a promising approach to address the issue of waste management and sustainable resource utilization in the seafood industry. This technology has been demonstrated to be effective in recovering high-value compounds such as proteins, lipids, and bioactive molecules from various seafood by-products, which can be further processed into various functional food and nutraceutical products. Fermentation technology offers several advantages over traditional chemical methods, including high selectivity, mild reaction conditions, and minimal environmental impact. Moreover, the use of microbial fermentation can provide a cost-effective and sustainable approach for recovering valuable compounds from seafood waste streams, as it can use low-cost substrates and operate at ambient temperatures and pressures. Several studies have demonstrated the potential of fermentation technology in extracting valuable compounds from different seafood by-products, such as fish skin, fish bones, and shrimp shells. For example, fish skin has been shown to be a rich source of collagen, which has been extracted through microbial

fermentation and used as a functional food ingredient. Similarly, shrimp shells have been utilized as a source of chitin and chitosan, which have various applications in the food and pharmaceutical industries.

In addition to extracting valuable compounds, fermentation technology can also be used to produce value-added products from seafood by-products. For instance, several studies have reported the use of fish waste as a substrate for the production of biogas and biofuels through anaerobic digestion and microbial fermentation. This approach can provide a sustainable and cost-effective alternative to traditional fossil fuels, which are finite and contribute to environmental degradation. Moreover, the use of fermentation technology for recovering valuable compounds from seafood waste streams can contribute to the circular economy concept, which aims to minimize waste and maximize resource utilization. By extracting and utilizing high-value compounds from seafood by-products, fermentation technology can reduce the environmental impact of the seafood industry, while creating new economic opportunities and value chains. However, there are also some challenges associated with the application of fermentation technology in the seafood industry. One of the main challenges is the diversity of seafood waste streams, which vary in their composition and properties. Therefore, developing customized fermentation processes for each waste stream can be time-consuming and resource-intensive. Additionally, the scale-up of fermentation processes from laboratory to industrial scale can also be challenging, as it requires optimization of various parameters, such as substrate concentration, fermentation time, and reactor design.

Another challenge is the competition for substrates between different microbial species, which can lead to reduced yields and selectivity of the fermentation process. Therefore, identifying and optimizing the growth conditions for the desired microbial strains can be crucial for the success of the fermentation process. Despite these challenges, the potential benefits of fermentation technology as a biorefining tool for recovering valuable nutrients from seafood side streams outweigh the limitations. This technology has the potential to contribute to a more sustainable and circular seafood industry, while creating new economic opportunities and reducing the environmental impact of seafood waste disposal. In conclusion, the application of fermentation technology for recovering valuable compounds from seafood waste streams is a promising approach for addressing the challenges of waste management and sustainable resource utilization in the seafood industry. However, further research is needed to optimize the fermentation processes and scale up the technology for industrial applications. Moreover, promoting the utilization of fermented seafood by-products as value-added ingredients in various food and nutraceutical products can also enhance the economic viability of the technology. Overall, the application of fermentation technology as a biorefining tool for recovering valuable nutrients from seafood side streams can contribute to a more sustainable and circular seafood industry, while creating new economic opportunities and reducing the environmental impact of seafood waste disposal.

Author contributions

S.A.S.—Validation, Formal Analysis, Resources, Writing—Original Draft, Writing—Review and Editing, Visualization, Data Curation, Project administration, Methodology, Investigation, Supervision. D.L.—Writing—Original Draft. C.P.—Investigation, Writing—Original Draft. Z.F.—Writing—Original Draft. R.C.M.—Formal Analysis, Funding. A.S.—Conceptualization, Writing—Review and Editing, Supervision.

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