Sustainable Food Technology

Accepted Manuscript

This article can be cited before page numbers have been issued, to do this please use: N. Thirugnanam, M. Chandran, P. A. Dattatrya and L. M., *Sustainable Food Technol.*, 2025, DOI: 10.1039/D5FB00784D.

ROYAL SOCIETY OF CHEMISTRY

View Article Online
DOI: 10.1039/D5FB00784D

Sustainability spotlight statement

The review titled "Harnessing non-thermal techniques for the sustainable protein extraction from blue foods and their potential applications in circular food systems" advances sustainable food systems by exploring non-thermal, energy-efficient technologies for protein extraction, highlighting its role as a green technology, as it does not add any negative impact to the environment than thermal processing does. The techniques, such as ultrasound, pulsed electric field, high-pressure processing, and enzyme-assisted extraction, help in minimizing waste generation and reducing chemical usage while improving yield and quality. By valorising marine biomass and underutilized aquatic species, this work supports the transformation of low-value by-products into high-value food ingredients, strengthening the foundation of a circular bioeconomy. The sustainable extraction of marine proteins also fosters biodiversity preservation and responsible resource management. The study aligns directly with the United Nations Sustainable Development Goals (SDGs), particularly SDG 12 (Responsible Consumption and Production), SDG 13 (Climate Action), and SDG 14 (Life Below Water), by promoting low-impact processing technologies that reduce environmental burdens. Furthermore, the proposed framework will serve as a basis for the exploration of the potential of integrating these eco-innovative technologies into industrial-scale applications, thereby reducing the dependence on land-based proteins and mitigating greenhouse gas emissions associated with conventional processing. The implementation of such sustainable extraction methods can contribute to food and nutritional security, promote circularity in marine-based industries, and establish a model for green innovation within the global food sector. Overall, this review highlights how non-thermal technologies can serve as transformative tools to achieve climate-resilient, waste-free, and resource-efficient food production systems.

Harnessing non-thermal techniques for the sustainable protein extraction from blue foods and their potential applications in circular food systems

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Abstract

Blue foods exhibit diverse group of aquatic resources and are essential for its nutritional profile including proteins and fatty acids and key micronutrients for human health. Numerous chemical and biological elements exist in marine habitats, which make the ocean a perfect source for high value compounds with multiple applications. Marine sources provide distinctive proteins, polysaccharides, along with micronutrients and bioactive compounds. Modern developments in non-thermal technologies facilitates environmentally friendly green and sustainable methods for the effective extraction of high value proteins from marine resources, which support environmental sustainable goals. The review focused on the optimistic effect of novel non-thermal treatments on protein from blue foods. It evaluates new processing methods that reduce waste and enhance protein extraction efficiency to produce functional products. The analysis identified the obstacles encountered during the production of marine proteins. The main goal is to reduce environmental effects by using unused marine biomass through energy efficient methods, which also generate less waste. Non-thermal processing methods enhance marine protein functionality and convert waste materials into food grade products to support circular bioeconomy models. These methods bring essential benefits to sustainable food systems by minimizing pollution and optimizing resource management. Sustainable marine protein extraction technologies support global biodiversity preservation, together with developing climate-resistant food innovations

Keywords: sustainable protein, non-thermal processing, marine bioresources, green technology, circular economy, environmental sustainability

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DOI: 10.1039/D5FB00784D

1. Introduction

A prevalent perspective suggests that the production of aquatic sustenance, termed as blue foods, obtained from marine and freshwater environments through capture or cultivation, must increase in the upcoming decades to meet the growing demand driven by population growth.[1] The blue food protein sector is gaining increased focus within the food sectors due to its abundance of high-quality ingredients that boast exceptional nutritional value and beneficial properties for health. Blue foods, encompassing both wild and cultivated items from marine and fresh water environments. It have been recently gained attention from scientists, nutritionists, private and public organizations. This interest stems from their potential to play a role in alleviating global hunger and ensuring nutritional security for humanity.[2] On a global scale, "blue foods" encompassing fish, invertebrates, and algae obtained from marine ecosystems play a vital role in ensuring the food and financial stability of billions of individuals. Serving as a pivotal source of protein, fatty acids, and micronutrients, these blue foods are indispensable in addressing challenges related to malnutrition and diseases.[3] The worldwide edible meat consumption from these blue foods is on the ascent, with a per capita consumption of 20.2 kg in the year 2020. The edible meat consumption from blue food constitutes 17% of animal protein which represent only sea and surpasses 50% in numerous Asian and African nations. In many regions, blue foods are not only more accessible but also more affordable compared to other animal-sourced proteins.[4] As the expansion of aquaculture persists, there is a corresponding need for aquafeeds that are both environmentally sustainable and cost-effective. This demand is projected to rise to 87 million tonnes by the year 2025.[5] Consequently, their production is on the rise, making them one of the most traded commodities globally and contributing to the support of jobs, livelihoods, and income on a worldwide scale.[4]

Ironically, while certain marine resources face over-exploitation or inefficient utilization for human sustenance, other abundant marine food sources remain largely untapped or are utilized primarily for producing feed for aquaculture or terrestrial animals. In general, there is a substantial loss, typically exceeding 90 per cent of nutritional value, such as proteins, at each tropic level in the food chain. Therefore, utilizing unexploited or underexploited blue foods directly for human consumption presents an ideal approach to optimize the use of our natural global resources, simultaneously addressing the challenge of feeding a growing population with nutritious food.[6,7] The challenges of a growing global population and increasing demand for protein sources through light on the utilization of marine proteins presents itself as a

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promising avenue for sustainable food production. Beyond their nutritional contribution, blue foods are increasingly recognized within global sustainability frameworks, particularly under the United Nations 2030 Agenda for Sustainable Development. Blue food systems directly contribute to Sustainable Development Goals (SDGs) 2 (Zero Hunger), 12 (Responsible Consumption and Production), 13 (Climate Action), and 14 (Life Below Water). Recent evidence suggests that strategic integration of blue foods into national dietary policies can simultaneously improve nutrition outcomes, reduce greenhouse gas emissions, and enhance livelihood resilience across coastal and low-income regions.[8] The Food and Agriculture Organization has further emphasized "blue transformation" as a pathway to reorient aquatic food systems toward sustainability, equity, and circular resource use.[9] Despite increasing production, blue food systems are characterized by significant inefficiencies, particularly during processing stages where 30–70% of biomass may become underutilized by-products such as heads, bones, skins, viscera, and shells. Conventional linear processing models often divert these residues toward low-value feed or landfill streams, resulting in nutrient losses and environmental burdens. Transitioning toward a circular bioeconomy framework, where protein, lipids, minerals, and bioactive compounds are sequentially recovered and valorised, can significantly reduce landfill burden, minimize nutrient loss, and improve overall resource efficiency.[5,10] Valorization of fish processing waste not only enhances economic returns but also contributes to climate mitigation through reduced waste decomposition emissions.

Several studies published in the past decade have concentrated on the beneficial applications of different aquatic species and their by-products mostly scales, bones, and skins to the production of collagen. These are the aquatic species' high-collagen materials. The primary sources of collagen in aquatic species (freshwater, deep-sea, and so forth) and processing circumstances (acid-aided, pepsin-aided, and so forth) were the primary sources of variation in aquatic species collagen.[11] The proteins from blue foods have a vital role as a functional and nutritional property in the food chain. The protein influences characteristics such as water absorption, oil absorption, foaming, emulsion, solubility, and texture of food.[12] Numerous food protein qualities can be improved or changed via the use of non-thermal technology. Protein coagulation, aggregation, or gelation can be modulated by these shifts created from non-thermal effects which enable varying degrees of unfolding and denaturation of the protein structure.[13] Marine-derived proteins are broadly classified into myofibrillar, sarcoplasmic, and stromal proteins, each contributing distinctly to the nutritional and techno-functional properties of blue foods. Myofibrillar proteins, primarily myosin and actin, play a crucial role in gel

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formation, water-holding capacity, and textural attributes, whereas sarcoplasmic proteins influence solubility and emulsification behaviour. The functional performance of these proteins is governed by their structural organization, including primary amino acid sequence, secondary folding patterns, and higher-order conformations. Processing parameters such as pH, ionic strength, temperature, and mechanical stress can significantly alter protein structure through denaturation, aggregation, or unfolding, thereby influencing extraction efficiency and end-use functionality.[13,14] Therefore, maintaining structural integrity during extraction is essential to preserve both nutritional quality and techno-functional characteristics. Recent studies have emphasized that advanced and non-conventional extraction technologies can enhance protein recovery while minimizing excessive structural degradation, thereby improving functional performance in food applications.[15] Beyond the functionality of intact proteins, controlled hydrolysis of marine proteins leads to the generation of bioactive peptides with enhanced biological activities. These peptides are produced through specific enzymatic cleavage of parent proteins and have been reported to exhibit antioxidant, antihypertensive, antimicrobial, and immunomodulatory properties. The production of such peptides further expands the utilization potential of blue biomass within food, pharmaceutical, and nutraceutical sectors.[14]

Several approaches have been developed to modify food proteins to improve their functional characteristics. These techniques include chemical methods (such as controlled enzymolysis, and chemical modification), physical methods (such as ultrasound, high-pressure treatment, pulsed electric field, and solvent extraction method), and hurdle techniques.[16,17,18] Conventional protein extraction techniques, such as strong acid or alkali solubilization, although effective, often require high chemical inputs, extensive water usage, and subsequent neutralization steps that increase environmental load. In contrast, non-thermal technologies, including ultrasound, pulsed electric field (PEF), high-pressure processing (HPP), and enzyme-assisted extraction, offer promising green alternatives. These approaches enhance cell disruption efficiency while operating at lower temperatures, thereby reducing energy demand and preserving protein functionality.[14,15] Moreover, enzyme-based and physical extraction methods minimize hazardous effluent generation and align more closely with sustainable processing principles. Such technologies, therefore, represent critical enablers in transitioning from linear extraction models toward environmentally responsible protein recovery systems.

Although several studies have investigated protein extraction from marine organisms, existing literature predominantly focuses on yield optimization and functional characterization, with

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limited integration of sustainability metrics, circular bioeconomy frameworks, and residue valorization strategies. Furthermore, comparative evaluation of conventional versus non-thermal extraction technologies from an environmental perspective remains underdeveloped.[14,19] There is a pressing need to critically examine how advanced extraction technologies can contribute to circular food systems while maintaining techno-functional performance. Therefore, this review aims to critically evaluate conventional and non-thermal protein extraction techniques from blue foods; analyse their sustainability implications, including energy demand and environmental footprint; explore circular bioeconomy integration through residue valorization pathways; and assess future opportunities within sustainable food systems.

2. Protein source from Blue-foods

The vitality of marine organisms as an originator of distinct proteins, fats, micronutrients, and bioactive substances continues escalating. Compounds obtained from marine organisms have emerged as a rich reservoir for exploring new peptides, although they remain relatively obscure due to the challenges associated with their retrieval. Marine peptides, constituting 8% of all bioactive marine compounds, play a significant role. A notable proportion of novel compounds have been identified from marine invertebrates, marine algae, and marine vertebrates (Fig.1.) in this section.

2.1. Algae-based sources for protein compounds

Most green and red macroalgae species have considerably higher protein content when compared with terrestrial plant protein sources such as soybeans, cereals, and nuts.[20] On top of their nutritional properties, the proteins and peptides derived from the marine algae have significant value because of their pharmaceutical, nutraceutical, and cosmeceutical properties like antioxidant property, immune modulatory property, anti-hypertensive property, and hepato-protective properties.[21] Brown seaweed has low protein content (3 to 15% of dry weight), whereas green and red seaweed demonstrate modest and high protein content of 9-26 and 47 per cent of dry weight respectively. A few examples are *Undaria pinnatifida, Ulva pertusa, Ulva lactuca, Porphyrayezoensis, Palmariapalmata, Laminaria digitata, Ulva rotundata, Ulva armoricana, Ulva rigida, Chondrus crispus, Ulva ohndi*.[22,23]

Microalgae act as an important source of bioactive molecules. They are loaded with carbohydrates, lipids, proteins, and minerals. Among microalgal species, some of the prominent classes are Cyanophyceae (blue-green algae), Bacillariophyceae (comprising

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diatoms), Chrysophyceae (encompassing golden algae) and Chlorophyceae (green algae) (24). Compare with macroalgae, microalgae have abundant number of proteins, which comprises around 70% of the biomass dry weight in some notable species.[25] Out of 50,000 species, only a few species of microalgae are considerably safe for human consumption such as Spirulina or *Arthrospira platensis, Chlorella* or *Chlorella vulgaris, Dunaliella, Nostoc, and Aphanizomenon.*[26] Microalgae act as an exceptionally prominent source of proteins for human consumption since the amino acid profile almost matches as that of human body.

2.2. Marine animal sources for protein compounds

The marine animal sources include vertebrates and invertebrates like sea urchins, sea anemones, starfish, cuttlefish, crabs, prawns, squid, octopus, jellyfish, and different variants of fish viz. carp, tilapia, marine eel fish, amur sturgeon, red drum fish, big eye snapper and giant croaker.[27,28,29] Nowadays, marine sources are scrutinized as one of the safest sources of protein. It also aids in reducing the risk of diseases like BSE (Bovine Spongiform Encephalopathy), TSE (Transmissible Spongiform Encephalopathy), and FMD (Foot and Mouth Disease) which may be caused due to the consumption of land-based animal-derived protein. These marine animals have high amounts of collagen which assists with the valorization of the fish waste.[27]

The aromatic (tryptophan, tyrosine, and phenylalanine) and nucleophilic amino acids with sulphur side chains (cysteine and methionine) are more efficient in terms of bioactivity of fish hydrolysates because of their ability to easily give away hydrogen atoms and interact with free radicals.[30] The most remarkable bioactivities of fish-based hydrolysates are determined by their amino acid composition, as well as structural and conformational properties.[31] Taurine, a conditionally essential amino acid, is particularly intriguing. Taurine's potential has been tailored for use as a therapeutic agent against congestive heart failure and a variety of other conditions, including blood pressure reduction, improved cardiac performance, and blood cholesterol reduction.[30]

Fish proteins are high in amino acids and peptides, making them highly digestible, especially in balanced proportions. The digestibility of amino acids and proteins is critical to the bioavailability and therapeutic efficacy of fish products.[32] Protein hydrolysis can produce bioactive peptides, particularly those derived from various fish species. The protein in oily and white fish undergoes breakdown into polypeptides, amino acids, and peptides. Bioactive chemicals are so named because the vast majority of them have bioactive properties. Bioactive

chemicals are additional nutritional ingredients found in foods that occur naturally in small amounts. These compounds have been found to be beneficial to human health.[33]

They can be transported through the intestinal enterocytes before reaching circulation, where they have beneficial biological effects. Peptides can deliver a wide range of biotechnological products with enhanced bioactivity, including antibacterial, antioxidant, and antihypertensive properties.[34] Lysine and methionine are two essential amino acids found in large amounts in fish protein. Angiotensin I converting enzyme (ACE) is a type of inhibitory peptide found in fish, originally in sardine flesh. Similarly, fatty fish have around 20% protein, but their water (62-70%) and oil levels are much higher (10-18%).[35]

3. Extraction of protein from Blue-foods

3.1. Conventional techniques for protein extraction

Conventional protein extraction methods include the pH shift process and solvent extraction. Acid and alkali solubilization methods are used for protein extraction under the pH shift process (Table.1). However, the most common extraction technique is the conventional techniques discussed in the following section (Fig.2).

3.1.1. pH shift processing for extraction of protein

pH shift process is the optimistic method in which the protein is extracted by altering the pH values more than its isoelectric point. In that condition, the protein will have a strong positive charge or negative charge, this will result in the repulsion of the charge causing the unfolding of the protein structure.[36] When the pH is modulated to the neutral pH, the proteins will get folded back into a molten state and there is an improvement in the functional properties.[37] Because of the unfolding and folding action, multiple subunits of proteins will get dissociated, increasing the solubility. Generally, food proteins are treated either with acid or alkali to attain extreme pH conditions, which creates a structural change in proteins.[16]

3.1.2. Acid extraction for isolation of protein

The collagen fibres are less soluble in the aqueous medium when compared with the acidic medium. The acid extraction includes treating the fishes and seaweeds with an acidic medium generally 0.5 M of Acetic acid, hydrochloric acid, lactic acid, citric acid, etc.[16] where the collagen obtained through this treatment is often called Acid Soluble Collagen (ACS).[27] Under acidic conditions, the bond between the collagen molecules is cleaved, which improves the

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extraction of collagen (Fig.3). When compared with the inorganic acids, the organic acids cleave the crosslink of the collagen molecules, yielding a higher extractability of the protein.[27] Under these conditions, there is repulsion between the tropocollagen molecules because of the positively charged collagen molecules, this phenomenon results in better solubilization.[38]

According to Pal & Suresh (2016), acid extraction can be conducted under high temperatures using 6 M hydrochloric acid for a period of 18 to 48 hours to get a resultant collagen from the fish.[39] Another study states that the fish is minced, and homogenized with cold water for 1 minute, and then, the pH is adjusted to 2.5 using 2 M HCl. Followed by, the mixture is kept at 4^0C and then it is centrifuged to get the soluble proteins. The yield of collagen is maximum (90 %) when the Baltic cod is treated with lactic acid or acetic acid when compared with HCl and citric acid which is around 18 and 60 per cent respectively.[27] The protein extraction of seaweed (*Ascophyllum nodosum*) was achieved by dissolving the seaweed in the distilled water and incubating it at 4^0C for 16 hrs. Further, the mixture is centrifuged to obtain pellets, which will be treated with HCl of different molarity in a 1:15 solid-to-solvent ratio. Later, the mixture was stirred and centrifuged to obtain the proteins

The interaction behaviour of collagen molecules was studied, where the aggregated state of collagen molecules and the acid concentration are inter-relatable. When the concentration of acid is increased, there is a better recovery of proteins. The rheological behaviour also depends on each other. The viscosity of collagen tends to decrease by increasing the acid concentration, resulting in the collagen's increased ability to flow.[40] Protein extracted by this method can be potentially used in commercial applications.

3.1.3.Alkali extraction for isolation of protein

In brief, alkali extraction is similar to acid extraction where the homogenized fishes are treated with high pH and it is accompanied by centrifugation to remove the higher-density particles from the solution. Then the proteins are allowed to precipitate by adjusting the pH to 5.5 and a second centrifugation is done to get the pure form of protein.[41] The recovery of sarcoplasmic and myofibrillar protein is higher in terms of the alkali shift process, these proteins will be washed off in the surimi process.[42] The alkaline pH provides higher solubilization of proteins than acidic pH so, the protein yield in alkali extraction is higher than that of the acid extraction.[12]

Several studies have concealed that the recovery of protein and solubilization is high in the pH above.[11] It clearly shows that the recovery of protein and the solubilization of protein mainly depends upon the pH value. If the pH value is higher, the consistency of the muscle will get lower, so that the phospholipid membranes will get separated leaving the protein during the first centrifugation which will increase the solubility of the protein.[43]

3.1.4. Solvent extraction for isolation of protein

The solvent used in the extraction will vary based on the target compound to get an efficient yield. This extraction may require a long duration depending upon the diffusion rate of solvents.[44] Based on the solvents, different solvent extractions are available. Among these processes, the Canadian process seemed to be effective which implies the extraction through isopropanol in a 2:1 solid-liquid ratio, yielding 19.94 percent. The defatted sample leads high quality of fish protein. Since proteins like insoluble collagen have hydrophobic and disulfide bonds, they rarely dissolve in an aqueous medium. By using high-reactive solvents like hydrogen peroxide, ethylene dichloride, and sodium hypochlorite, the amino acid profile may alter, resulting in the formation of toxic peptides and choline derivatives.[45]

A concept called Deep Eutectic Solvent Extraction (DES) is applied in the extraction of proteins, where two different solvents are used together, a hydrogen bond donor and a hydrogen bond acceptor respectively.[40] According to Bai, (2017), the extraction yield was maximum when the extraction was done with choline chloride and oxalic acid among six different methods.[46] In further studies, it was found that the extraction yield of protein would be higher by increasing the amount of oxalic acid and keeping the choline chloride constant. It can be used as a sustainable extraction of collagen.[40]

3.2. Advanced techniques for protein extraction

The sustainable alternate protein from blue foods can be extracted using advanced and eco-friendly techniques like enzyme-assisted, sonication, pulsed electric field, and high pressure processing (Table.1). The influence of advanced techniques on protein extraction efficiency has been discussed in the following sections.

3.2.1 Enzyme-Assisted Extraction Technique for proteins from blue foods

Enzyme-assisted extraction utilizes specific proteases or cell wall-degrading enzymes to hydrolyse structural components, thereby improving protein solubilization under mild

conditions. The efficiency of enzymatic extraction depends on enzyme specificity, enzyme-to-substrate ratio, pH, temperature, and reaction time.[19] Enzymatic hydrolysis of fish protein and other marine foods has attracted greater attention recently as a technique for producing high-quality FPH (Fish Protein Hydrolysates) that may be a desirable raw material for making bioactive peptides to treat various diseases and disorders. FPH obtained by this method provides a wide range of applications and nutrition such as dietary supplements, pharmaceuticals, animal nutrition, and cosmetics.[47] The protease enzymes have been used to hydrolyse fish. Proteins like Neutrase, Flavourzyme, Papain, Alcalase, and Bromilane have been used commercially.

For instance, demonstrated that enzyme-assisted extraction methods successfully extract bioactive compounds from seaweeds and microalgae used in the nutraceutical industry.[48] Similarly, accomplished the extraction and identification of proteins from the red seaweed *Palmaria palmata*, which resulted in better yield and improved functional properties.[49] Enzyme-assisted methods have been used to extract materials from fish and fish by-products. Wang, (2020) developed antioxidant-rich protein hydrolysates from cobia liver through enzymatic hydrolysis.[50] The successful extraction of protein and fish oil from Baltic herring by employing proteolytic enzymes.[51] Thus, the extracted proteins from fish backbones through a combination of steam explosion methods and enzymatic hydrolysis. Fish backbone proteins increased through the combined use of steam explosion and enzymatic hydrolysis.[51,52]

Tran, (2023) demonstrated that Basa fish skin collagen extraction through enzymatic hydrolysis maintained the bioactivity and structural integrity of collagen peptides. Appropriate enzyme choice alongside processing duration and conditions determines both product quantity and protein quality.[53] The enzyme-assisted extraction method presents multiple benefits over traditional solvent-based techniques by speeding up processing times and reducing harmful chemical use while enhancing environmental sustainability. Enzyme-assisted extraction has become a leading method to maximize blue food resources and fulfil the rising demand for functional and bioactive protein ingredients.

3.2.2. Ultrasound-Assisted Extraction Technique for blue foods

Ultrasound waves are mechanical waves that can travel through solid, gaseous, and liquid media by rarefaction and compression. When the pressure generated by this expansion is greater than the liquid's tensile strength, it causes negative pressures in liquids that eventually result in the creation of vapor bubbles. Bubble cavitation is the implosive collapse of vapor

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bubbles. Macro turbulence, high-velocity inter-particle collisions, and micro-porous structure are produced by cavitation, which enhances matrix permeability and facilitates optimal solvent permeation into the cell's matrix, enabling target chemicals to interact with the solvent and streamlining the extraction process.[54]

Ultrasonic wave vibration creates cavitation. A phenomenon of dissipation of energy that spreads throughout the medium through the development and ensuing disintegration of vapor bubbles. Cavitation additionally raises the kinetic energy of the particles within the treated substance (Fig.4.). As a result of the ultrasonic energy's shock effect during the extraction process, high temperature offers enough energy for a reaction.[55] Numerous intra- and intermolecular covalent cross-links involving lysine and hydroxylysine residues, ester bonds, and other interactions with saccharides must be broken during collagen extraction. Mass transportation in wet processes is improved by ultrasonication.

Among all the proteins, collagen is the most abundant structural protein which accounts for about 25-30 percent and is found in the animal body. Collagen consists of a large molecule that has a triple helical structure with each polypeptide chain mostly containing repeating units of glycine, proline, and hydroxyproline.[56] It has been observed that conventional methods are prolonged processes and collagen residue tissue will be more, in addition to that, a high amount of insoluble collagens will be left behind.[56] The ultrasonication technique is non-destructive and non-invasive, the good quality of protein can be obtained without interrupting the molecular structure of collagen.[57] To extract collagen from various marine sources such as clown feather back, golden carp, sea bass, soft-shelled turtle, and grass carp calipash the ultrasonication method has been used.

Moreover, ultrasonication reduces the size of collagen particles despite increasing their pH and salt-induced solubility.[58] Even though ultrasonication is a favourable and propitious technology to enhance the quality and amount of resulting collagen, the amplitudes and extraction times need to be carefully regulated. The use of ultrasonication in collagen extraction can shorten extraction times and improve the quality and quantity of collagen recovered. Low-intensity ultrasound alters the state of bacteria and promotes their development by causing repairable damage and stable cavitation.[59] Furthermore, water molecules may be broken down more easily by ultrasound, which can potentially generate free radicals and damage bacterial DNA and enzymes.[60]

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Even though ultrasonication has many advantages, prolonged use of the technology results in a cavitation effect, which raises the temperature, shear force, and pressure of the medium and breaks hydrogen bonds and van der waals interactions in polypeptide chains, and this denaturizes proteins and enzymes.[54]

3.2.3. HPP Treatment for Protein Extraction from Blue Foods

A non-thermal technology called high-pressure processing (HPP) has been adopted to alter or improve the protein characteristics in a variety of foods.[61] It is one of the novel technologies and is considered an environmentally friendly technique.[62] HPP is a technique where high pressure is carried out on the sample up to 1000 MPa in the presence or absence of heat. It has been reported that when HPP treatment is implemented on the desired marine food product, there is a significant increase in the yield of gelatin protein, and it also shortens the extraction time.[13] This is because, during pre-treatment, the pressure ruptures the bond between the secondary, tertiary, and quaternary structures of the gelatin protein, which aids in the release of more peptide bonds soon after thermal hydrolysis.[63] The protein coagulation, aggregation, or gelation can change as a result of the modifications, which allow changing the protein structure via unfolding and denaturation to varying degrees (Fig.5).[13] According to several studies, myosin starts to unwind at pressures of about 50 MPa. The tertiary and secondary structures of myosin also tend to unfold when high pressure (100MPa) is applied.[64] These pressure levels may trigger the myosin's solubilization and denaturation, which are essential for the formation of protein gelation. However, the amount of pressure given to the meat product will determine how much of the protein unfolds.[65]

HPP has the ability to break down the cell wall of both gram-positive and gram-negative bacteria to facilitate more amount of protein yield through extraction. The interaction of side-to-side chains through covalent and non-covalent bonding promotes aggregation and gelation, when HPP is introduced to myosin. Gels are subjected to pressure treatments that encourage the formation of non-covalent linkages.[13] The development of a uniform and smooth gel structure contributed to the growth of the myosin matrix, which was significantly enhanced by the use of 300 MPa. Additionally, modifications to the structure of myofibrillar proteins may have an impact on the quality of meat products and the textural characteristics and properties of gels.[66] HPP enhances the gelling property in marine foods.

3.2.4.Pulsed electric field for protein extraction from blue foods

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The pulsed electric field can facilitate the extraction of protein from blue foods by inducing electric currents with high voltage from an electric field within micro to milliseconds.[67] Through reversible or irreversible electroporation (Fig.6), the electric current will enter the cell wall, resulting in the release of intracellular components, including protein, DNA, carbohydrates, lipids, and micronutrients. Critical influencing factors include electric field strength, pulse duration, number of pulses, and conductivity of the extraction medium.[68]

According to Buchmann, (2019) found the interrelationship between the strength of the electric field and the concentration of protein being extracted from *Chlorella vulgaris* treated in 20 $kVcm^{-1}$electric field strength.[69] As an instance from the study, the protein concentration was 0.55±0.01g L^{-1} in electric field strength of 10 kV cm^{-1} and increased to 0.80±0.04 g L^{-1} in 20 kV cm^{-1}, resulting in the average protein extraction increased with the electric field strength. Some studies showed that the PEF is not feasible yet for the extraction of selectively proteins alone, because it will not completely disintegrate the cell wall.[70] Polikovsky, (2016) demonstrated the extraction of selective proteins through PEF where the yield of specific proteins is greater. By allowing the extraction of intact cytosolic proteins, there was a notable increase in protein extraction of *C.Vulgaris* and *Nannochloropsis salina*.[71]

3.2.5. Supercritical fluid (SCF) extraction for protein isolation from blue foods

Supercritical fluid extraction is a green technology that utilizes carbon dioxide which can act as a fluid at a certain temperature and pressure above its critical point.[72] Jafari, (2020) found that the yield of protein from the cod skin was 13.8 per cent through SCF which was relatively higher than the acid and pepsin-aided AcOH extraction (5.72 and 11.14% respectively).[40] Considerably, Supercritical fluid extraction is used in the selective extraction of bioactive proteins and peptides from the plant substrates whereas, the extraction of protein from seaweed is limited by SCF, and presently studies are focusing in this direction for better extraction and characteristics.[67]

3.2.6. Hurdle technology for synergistic effect in protein extraction

PEF and Enzymatic extraction: In the combination of PEF and enzymatic extraction, PEF could reduce the foaming properties and enhance the emulsifying properties and the solubility of the protein from the Abalone viscera, resulting in a promising yield. A study showed that the yield of combined treatment is higher than the pure enzymatic extraction.[73]

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PEF And Mechanical Press: In this extraction process, PEF is coupled with a mechanical press, where 200 pulses having a field strength of 1kV/cm were applied to *Ulva ohndi.* The duration and repetition of pulses were 50µs and 3Hz respectively. It was done concurrently with the mechanical pressing at 107,682 N/m^2. Around 14.94 per cent yield of protein was obtained through this extraction.[23]

PEF and Hydraulic Pressure: According to Polikovsky, (2016), the biomass of *Ulva* sp., was submerged in deionized water and 75 pulses with a field strength of 2.964 kV/cm were applied to the solution with a pulse repetition rate of 0.5Hz and 5.70µs of pulse duration. The extraction was combined with hydraulic pressing for 5 min under the pressure of 450 N/cm^2. The total protein concentration of the extract after treatment is 59.13±3.82 µgmL^{-1} which is higher than the untreated sample.[21] The advanced non-thermal approach leads optimistic nutritional and functional characteristics (Table 2) can be utilized for enhanced protein extraction from blue foods. The hybrid techniques pave a new direction for researchers to obtain synergistic effects in blue foods.

4. Factors affecting protein from blue foods and their mitigations

4.1. Impurities on protein purity

Even though Algae are rich in protein, they also tend to gather toxic heavy metals like mercury, lead, arsenic, and cadmium. The appearance of lead and mercury is under the legal limit for safe human consumption, whereas arsenic and cadmium presence are above the legal limits. There is a chance of protein contamination with heavy metals when extracted from algae. There is an acceptable level of heavy metal in the case of microalgae.[68]

4.2. Food allergenicity as a barrier for protein consumption

Protein consumption faces significant obstacles because food allergies trigger immune responses that can be either IgE-mediated or non-IgE-mediated. The release of histamine through IgE-mediated allergies produces symptoms spanning the skin and the respiratory, digestive, and circulatory systems.[74,75] Food allergies affect 2.5% of people worldwide, while fish represents one of the main allergenic sources. The WHO/IUIS has recognized 12 fish proteins as allergens, which include parvalbumin along with tropomyosin and aldolase A. People who develop fish allergies typically have symptoms that last throughout their lives, although the severity changes over time. The fish species cod, salmon, and mackerel contain parvalbumin, which serves as a primary allergen. Protein structures undergo changes due to

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processing methods like drying, heating, and smoking, which can influence their potential to cause allergic reactions.[76]

The effects of processing methods on allergenicity depend on the specific protein matrix structure, alongside detection techniques and antibody specificity. Experimental findings from ELISA and Western blotting indicate that thermal processing alters IgE protein binding patterns. IgE binding to heated whiff parvalbumin vanishes rapidly during digestion, but remains in some cases after extended heating periods.[77,78] Allergenicity varies based on demographic factors such as age, gender, region, and ethnicity, which show increased prevalence in Asian populations as well as females and adult individuals.

4.3. Economic perspective on commercial usage

The commercialization of microalgae to extract proteins was found to be a challenge.[79] The cost of microalgae production will vary depending on the upstream process and downstream processes. Some studies showed that microalgae can be cultivated in wastewater, but that will result in the contamination of the produce, and it can't be used in foods.[80] To get better growth of microalgae, photobioreactors can be used, but the operating costs for this reactor are high. The development of some robust processes is needed for the commercialization of microalgae.[81]

4.4. Environmental Sustainability

To enhance transparency in the environmental sustainability discussion, the carbon footprint considerations presented in this review follow a cradle-to-gate system boundary. This includes raw material acquisition from blue food sources, pre-treatment processes, non-thermal extraction stages, and subsequent drying operations, while excluding downstream processes such as packaging, distribution, retail handling, consumer use, and end-of-life disposal. Such boundary definition aligns with standardized environmental assessment approaches applied in food system evaluations.[82] The functional unit was defined as 1 kg of isolated protein produced, ensuring comparability with food-system-level sustainability metrics reported for blue foods.[2,8]

Carbon emission estimations were primarily based on reported energy consumption associated with non-thermal technologies including ultrasound, pulsed electric field, and high-pressure processing. Emissions were conceptually calculated by multiplying energy demand (kWh) by corresponding carbon intensity factors of electricity, consistent with carbon footprint frameworks used in food basket and resource assessment studies.[82] Assumptions include

average industrial electricity consumption, partial water reuse during extraction, and solvent recovery efficiencies where applicable. Capital equipment manufacturing and transportation emissions were excluded due to limited reporting across extraction studies. By explicitly defining system boundaries, functional unit, and calculation approach, the environmental discussion is aligned with broader sustainability assessments of blue foods and global food systems, thereby improving clarity, transparency, and methodological consistency.[2,8]

5. Applications of protein from blue foods

The aquatic ecosystem is still unexploited reservoir of many nutritional and functional components. Though, the marine protein (collagen) plays a vital application in pharmaceutical, food, and cosmetic and other domains. The food-based application of protein from blue foods has been highlighted in this review.

5.1.Taylor-made foods / Functional foods from blue foods

The algal proteins are incorporated into foods due to their nutritional and sensorial properties and also to overcome the challenges of the low dispersibility of proteins. The algal proteins are used in the formulation of Yogurt with *A. plantensis* and pasta with *C. vulgaris* and *A. maxima*.[83,84] The microalgal proteins have foaming, emulsifying, and stabilizing properties, which shows the advantages over plant proteins.[81]

Some studies showed that bread can be enriched with fish proteins through different formulations. The acceptability rate was also high and this showed that there was not much difference in the sensorial properties of bread.[85]

5.2. Nutraceuticals from aquatic organisms

Natural bioactive compounds with therapeutic benefits, called nutraceuticals, are becoming more popular as synthetic drug substitutes because disease rates continue to rise. Shrimp processing generates 40–50% biomass waste, which is considered valuable among aquatic sources. Shrimp waste contains high levels of astaxanthin ($C_{40}H_{52}O_4$), which acts as a powerful antioxidant while giving shrimp meat its red color and making up 65–98% of its total carotenoid content.[86] Each year, India generates over 15,000 tonnes of shrimp waste, which represents a significant potential for resource recovery.[87]

Feed microalgae-derived β-carotene or zeaxanthin undergoes oxidative conversion to create astaxanthin, which holds substantial commercial importance in both food and pharmaceutical

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sectors.[88] The process of extracting astaxanthin from crustacean waste achieves sustainable waste management goals while meeting increasing market needs for natural dietary supplements. Product consistency and global market needs present major challenges to scaling shrimp-waste-based nutraceutical production.

5.3. Valorization of biowaste from marine sources

Generally, macroalgae are used as a feasible feedstock for biomass. The challenging one is the fractionation of biomass; some sustainable processes and methods are needed to upscale it. Without the fractionation, the algae will become waste. To reduce that, PEF coupled with mechanical pressing is applied to the macroalgae (*U. ohnoi)* for the extraction of a wholesome amount of proteins.[23]

The optimization of low-value foods and underutilized foods is necessary to avoid wastage. The underutilized fish can be used to extract the proteins. Through this, the underutilized fish will be converted into valuable ones. Further, the fish proteins can be incorporated into the foods.[89]

5.4 Sustainable animal feed and aquafeed

Blue food-derived protein hydrolysates, which are typically by-products, present nutritious and sustainable feed options for animals and aquaculture that yield better results. Protein hydrolysates contain abundant bioavailable amino acids and bioactive peptides that support animal growth performance and immunity while improving nutrient absorption. The process of enzyme-assisted hydrolysis produces fish protein hydrolysates from sardine by-products and marine wastes, which deliver high-quality feed supplements having minimal environmental impact.[47] These protein compounds exhibit functional advantages through their antioxidant and antimicrobial properties, which enhance animal well-being and lessen antibiotic dependence in feed.[45]

Aquaculture systems can use fish protein hydrolysates to replace traditional fishmeal either partially or completely, which helps to reduce the exploitation of wild fish stocks. For example, microalgal proteins extracted through non-thermal methods, such as pulsed electric field or enzymatic hydrolysis, show great potential for use in aquafeeds.[81] Alternative protein sources have exhibited excellent digestibility and palatability while offering a balanced profile of amino acids.

The residual biomass from blue food production, including seaweed residues and microalgal cell walls, can be transformed into feed components or bio-stimulants for use in integrated aquaculture systems.[68] The examined methods for transforming algal residues with high structural carbohydrate and protein content into viable dietary components for fish and shrimp following proper processing. Nutrient sources from these residues also support gut health and maintain microbial balance among aquatic organisms.

5.6. Potential Medical Applications from Marine Sources

Proteins, peptides, and amino acids obtained from marine sources possess enormous potential for advanced biomedical research, providing insight into the workings of both healthy and diseased human bodies. Moreover, they provide the potential to create highly targeted and effective medications to treat a range of illnesses. Consider collagen that has been taken from some marine mammals, for example. Tissue-like structures in 3D bioprinting are often built on collagen, a structural protein essential for many body tissues. These collagen scaffolds are very useful for tissue engineering applications, such as blood vessel, skin, and bone regeneration.[90]

Furthermore, collagen is an invaluable medical excipient due to its exceptional qualities, which include low antigenicity and biocompatibility. It has several uses, including drug transport capsules, bone tissue regeneration fillers, and deionized membranes in surgery. When introduced into the body, these membranes work well with host cells and tissues, reducing negative immune reactions.[91] Collagen is biodegradable and naturally absorbed by the body.[92]

5.8. Innovative food products

Marine proteins have become popular in the food industry due to their high nutritional value. Collagen from marine animals is used to make gelatin, a versatile Ingredient.[93] Gelatin is a major component in many delicious desserts, such as fudge, puddings, marshmallows, and salads. Algal proteins, rich in amino acids and readily digestible, have been incorporated into innovative food products.[94] These proteins are incorporated into vegan meat substitutes, protein-rich snacks, and dairy alternatives. Protein derived from edible microalgae like *Isochrisis galbana* and *Chlorella vulgaris* shows potential as food supplements and additives. Phycobiliproteins from *Porphyridium cruentum* (red algae) and *Synechococcus spp*. (blue-green algae) have been utilized as natural food colorants. These specialized protein groups have been integrated into various food products, including dairy, chewing gums, jellies, and ice sherbaths, to serve as colouring agents.[92]

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5.9. Residue Valorization and Circular Bioeconomy

Protein extraction from blue biomass generates significant residual fractions which are still rich in lipids, minerals, collagen, chitin, and other bioactive compounds. These residues should not be considered as waste, as they possess high biological and commercial value. Effective utilization of these fractions plays a vital role in strengthening the circular bioeconomy model and improving sustainability of the blue food supply chain.[5] The lipid fraction remaining after protein extraction may contain long-chain omega-3 fatty acids such as EPA and DHA which are widely used in nutraceutical and functional food formulations. Tuna processing side streams have been successfully utilized for recovery of proteins, lipids, and minerals through integrated biorefinery approaches, thereby reducing environmental burden and enhancing economic return.[95] Similarly, invasive marine species such as blue crab (*Callinectes sapidus*) have been valorised into high-value nutritional ingredients and bioactive compounds, converting ecological challenges into sustainable opportunities.[96,97]

Collagen and gelatin extracted from fish skin, bones, and connective tissues have wide applications in food, pharmaceutical, and biomedical industries due to their functional and structural properties. Mineral-rich residues, particularly from bivalve shells and crustacean exoskeletons, are important sources of calcium carbonate and chitin. Valorization of shell waste has gained attention within circular blue bioeconomy strategies for applications in agriculture, environmental remediation, and material science.[98] Moreover, the remaining biomass after sequential extraction can be utilized as an animal feed ingredient or converted into bioenergy through anaerobic digestion, thereby reducing landfill accumulation and greenhouse gas emissions. Integration of protein extraction into a multi-product biorefinery framework enables the cascading utilization of marine biomass and supports sustainable, circular food systems.[99]

6. Practical and Industrial Challenges in the Application of Isolated Blue Food Proteins

Despite the promising functional and nutritional attributes of isolated proteins derived from blue foods, several practical and industrial challenges remain that may limit their large-scale implementation. One major limitation involves variability in raw material composition, which can significantly influence protein yield, purity, and techno-functional performance.[81,100] Seasonal variation, species diversity, and environmental conditions affect protein structure and extractability, thereby complicating process standardization. Furthermore, purification and isolation technologies often require multiple processing steps, including membrane filtration,

precipitation, and chromatographic separation, which increase operational costs and energy demand.[101] Although non-thermal techniques improve extraction efficiency, scale-up feasibility and equipment investment remain critical constraints.

In addition, structural modifications occurring during extraction and drying may alter solubility, emulsifying capacity, and gelation behaviour, potentially limiting functional performance in complex food matrices.[102,103] Sensory challenges, including off-flavors, color instability, and marine-associated aromas, can also affect consumer acceptance, particularly in mainstream food applications.[104] Regulatory considerations, allergenicity assessments, and labelling requirements further complicate commercialization pathways for novel protein ingredients. Therefore, while isolated blue food proteins demonstrate considerable potential for sustainable food system transformation, addressing techno-economic feasibility, sensory optimization, and regulatory compliance is essential for successful real-world adoption.

7. Conclusion, limitations, and Future Perspective

This review has explored the innovative techniques for protein extraction from blue foods based on the concept of non-thermal techniques, which are a safe, green approach, with less treatment time, and can enhance the extraction efficiency of protein with supreme quality. The protein from marine sources can be commercialized for its virtuous approach, specifically nutraceuticals and bioactive compounds. There is a projected substantial market for food products, supplements, and natural health products containing marine bioactive due to a multitude of possible health benefits. Despite providing a comprehensive overview of non-thermal techniques for sustainable protein extraction from blue foods, this review is limited by the availability of large-scale industrial data and standardized environmental assessment metrics across studies. Variations in reported extraction efficiencies, functional properties, and processing conditions restrict direct quantitative comparisons. Additionally, techno-economic feasibility and long-term storage stability remain underexplored in the current literature, highlighting the need for pilot-scale validation and integrated life cycle assessments in future research. The review directs future research and development on modified protein, or bioactive compounds, into foods for prominence, as these components have significant nutritional and functional benefits in addressing various health concerns. In the future, the commercialization process will gain advantages through the application of biorefinery approaches, which aim to create cost-effective and environmentally friendly extraction methods for generating bioactive compounds with well-measured beneficial effects. Innovative non-thermal technologies have

arisen as green approaches, promising, safe, and efficient methods for retrieving high-quality nutritional components, specifically protein. These modified proteins have optimistic structural and functional properties that can be commercially utilized as functional ingredients.

Conflict of interest

The authors stated that there is no conflict of interest.

Abbreviations

Abbreviate	Expansion
3D	Three Dimensional
ACS	Acid Soluble Collagen
BSE	Bovine Spongiform Encephalopathy
DES	Deep Eutectic Solvent
DNA	Deoxyribonucleic Acid
ELISA	Enzyme-Linked Immunosorbent Assay
FMD	Foot and Mouth Disease
FPH	Fish Protein Hydrolysates
HPP	High-Pressure Processing
HVAC	High Value Compounds
IUIS	International Union of Immunological Societies
PEF	Pulsed Electric Field
SCF	Super Critical Fluid
TSE	Transmissible Spongiform Encephalopathy
WHO	World Health Organisation

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DOI: 10.1039/D5FB00784D

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DOI: 10.1039/D5FB00784D

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Table 1. Extraction of Protein from blue foods with different methods

Sources	Method of extraction	Extraction conditions	Yield (%)	Reference
Algae				
Microalgae				
Aglaothamnion uruguayense	Alkali extraction	Addition of 1mL 0.1N NaOH to the centrifuged pellet with occasional shaking	22.38	105
*Hillea*sp.	Alkali extraction	Addition of 1mL 0.1N NaOH to the centrifuged pellet with occasional shaking	25.04	105
Amphidinium carterae	Alkali extraction	Addition of 1mL 0.1N NaOH to the centrifuged pellet with occasional shaking	24.06	105
Haematococcus pluvialis	Ultrasonication	Frequency-20 kHz, 5 s cycles with 15 s of resting time for 30 min	8.5±0.0	106
Porphyridium cruentum	Ultrasonication	Frequency-20 kHz, 5 s cycles with 15 s of resting time for 30 min	67.0 ± 0.9	106

Arthrospira platensis	High pressure homogenization (HPH)	2700 bar pressure in two passes	78.0 ± 2.8	106
Macroalgae				
Ulva ohnoi	PEF coupled with a mechanical press	200 pulses with a field strength of 1kV/cm, repetition rate and pulse duration 3 Hz and 50 µs, and combined with mechanical pressing at 107,682 N/m2	14.94	23
Ulva armoricana	Enzyme assisted extraction	6% endoprotease enzyme, soaked at 50^{0}C for 3h	41.40	107
Chondracanthus Chamissoi	Enzyme assisted extraction	Cellulase enzyme, pH 4.5, for 12h at 50^{0}C, 1:10 enzyme-solvent ratio	36.10	108
Gracilaria sp.	Ultrasound-assisted alkaline extraction	Suspension of sample in 10% (v/v) NaOH, sonication for 2h, further filtration (0.45µm), and dialysis (2kDa) is done	86	109
Ascophyllum Nodosum	sequential acid-alkaline extraction	0.4 M HCl for 1h at 4^{0}C & 0.4 M NaOH for 1h at 4^{0}C	59.75	110

Fucus vesiculosus	HPP	600 MPa for 40 min, followed by filtration	23.7	111
Chlorella vulgaris	PEF with bead milling	14 pulses with a field strength of 20.6 kV cm^{-1} and tip speed of 8 ms^{-1}	~30 protein release	70
Neochloris Oleoabundans	PEF with bead milling	14 pulses with a field strength of 19.7 kV cm^{-1} and tip speed of 8 ms^{-1}	~50 protein release	70
Ulva sp.	Enzyme-assisted PEF extraction	Enzyme pretreatment with Cellulase Onzuka R-10, 30 pulses with the field strength of 1kV cm^{-1}, pulse duration, and repetition rate is 30 µs and 5 Hz	19.6±0.33	112
Gracilaria verrucosa	Enzymatic extraction	Agarase + Cellulase, 2 h and 14 h incubation	63% - 2 h 21% - 14 h	113
Chondrus crispus	Enzymatic extraction	Carrageenase + Cellulase, 2 h and 14 h incubation	32% - 2 h and 14 h	113

Marine animals				
Yellowfin Tuna *Thunnus albacares*	Acid extraction	0.5 M acetic acid in a sample-solvent ratio of 1:10 for 48 h at 4^0C	1.07	114
Grass carp *Ctenopharyngodon idella*	Acid extraction	0.5 M acetic acid in a sample-solvent ratio of 1:10 for 72 h at 4^0C	90	115
Catla *Catlacatla*	Acid extraction	0.5 M acetic acid in a sample-solvent ratio of 1:10 for 24 h at 4^0C	63	116
Rohu *Labeorohita*	Acid extraction	0.5 M acetic acid in a sample-solvent ratio of 1:10 for 24 h at 4^0C	46	116
Small spotted catshark *Scyliorhinus canicula*	Acid extraction	0.5 M acetic acid at 25^0C for 24 h	61.24	117
Thornback ray *Raja clavata*	Pepsin-aided acid extraction	0.5 M acetic acid in a sample solvent ratio of 1:10, followed by the addition of 5g of pepsin/g, T=4^0C for 18h	30.16	118

Red drum fish *(Sciaenops ocellatus)*	Pepsin-aided acid extraction	15 l of 1 M acetic acid, 0.5% pepsin, t = 8 h	4.32±0.30	29
Mackerel	Isoelectric solubilization precipitation	0.2 M NaOH in 1:10 sample-solvent ratio	48.08±0.04	54
Starfish	A combination of Ultrasound and High-shear mechanical homogenization	0.1 M NaOH in 1:10 sample solvent ratio, 4000 rpm for 2.5 min, 70% amplitude for 10 min	3.37±0.10	56
Golden carp *(Probarbusjullieni)*	Ultrasound assisted acid extraction	Acid pretreatment in 1:10 sample solvent ratio, 20 Hz frequency, 80% amplitude for 30 mins	81.53	119
Clown featherback *(Chitala ornate)*	Ultrasound-assisted extraction	750 W, f = 20 kHz, 20,40,60,and 80% amplitude with different time intervals 10,20,30 min	27.18 to 57.35	120
Jellyfish (*Acromitushardenbergi)*	Acid extraction	0.5M acetic acid (1:1000 w/v)	65.20±1.12	121

Table 2. Functional properties of modified Protein from blue foods using novel techniques

S.No	Treatments	Sources	Functional Property	Reference
1.	Ultrasound-assisted extraction	*Spirulina platensis*	WAC, OAC, EA, ES, FC. FS	122
2.	Osmotic shock + Ultrasound	*Chlorella vulgaris*	WAC, OAC, EA, ES, FC, FS	123
3.	Isoelectric precipitation	*Loligo vulgaris*	FC, FS, ES, FBC, WHC	124
4.	HPP	*Callinectes sapidus*	WBC	125
5.	Ultrasound-assisted extraction	*Dosidicus gigas*	FC, FS	126
6.	PEF	*Haliotis discus hannai*ino	FC, FS, EA, ES	73
7.	HPP	Blue crab	Gelation property	13
8.	Ultrasound-assisted extraction	*Dasyatiszugei*	Viscosity, RP, WHC, ES	57
9.	Ultrasound-assisted extraction	Tuna	WHC, ES, EA, Viscosity	58

Where WHC-Water Holding Capacity, WAC-Water Absorption Capacity, ES-Emulsion Stability, EA-Emulsifying Activity, RP-Rheological Property, FC-Foaming Capacity, FS-Foaming Stability, OAC-Oil Absorption Capacity, FBC-Fat Binding Capacity

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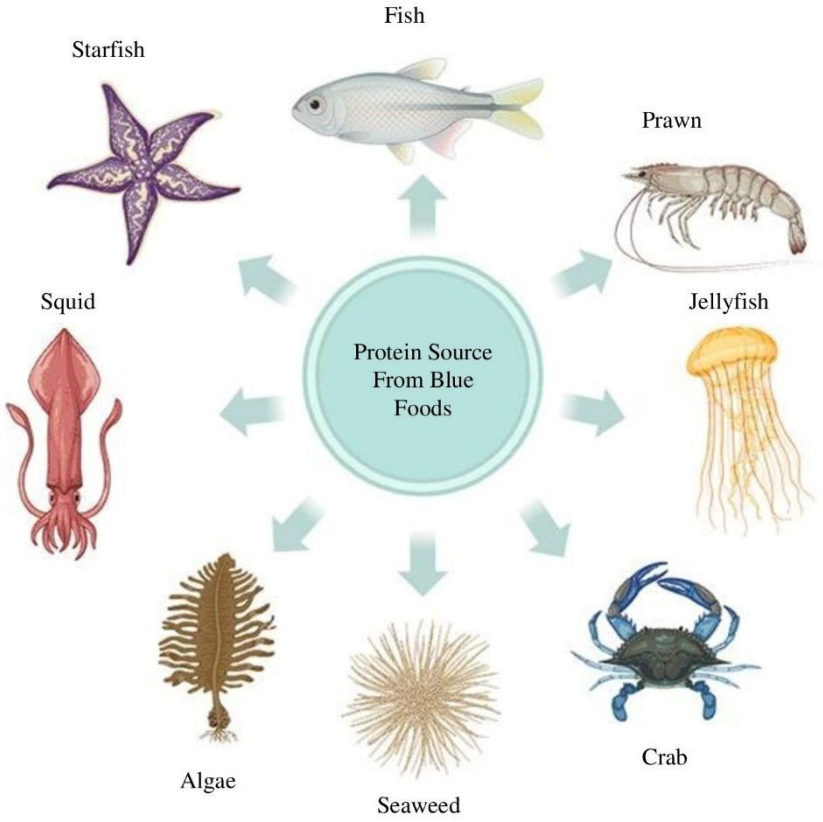

Fig.1. Protein sources from blue foods

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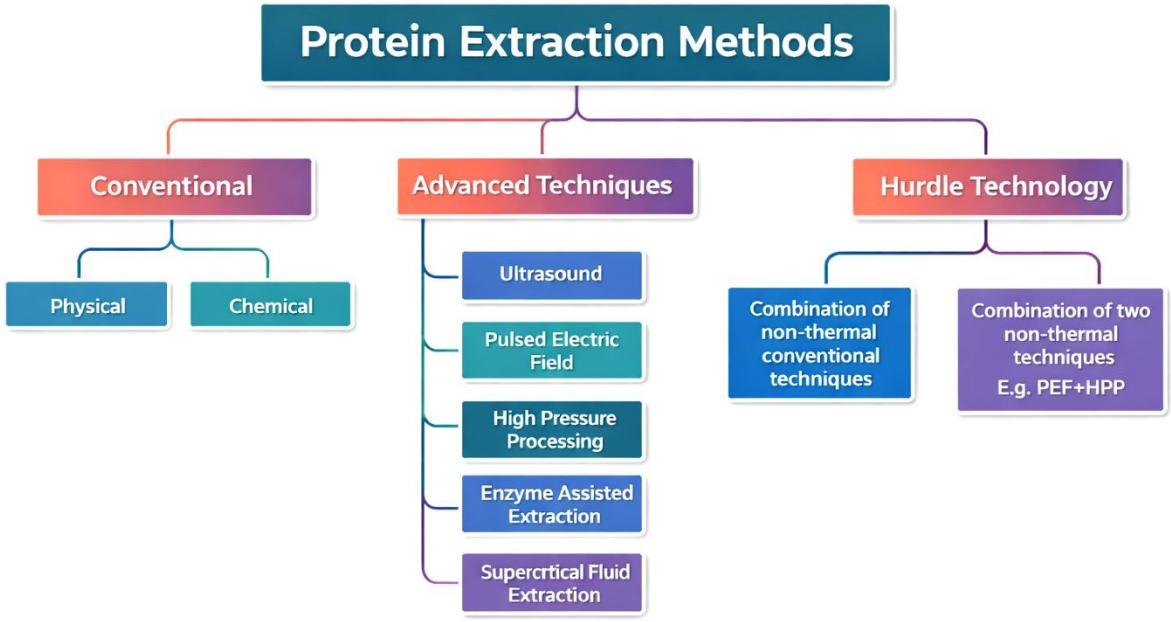

Fig.2. Protein extraction methods

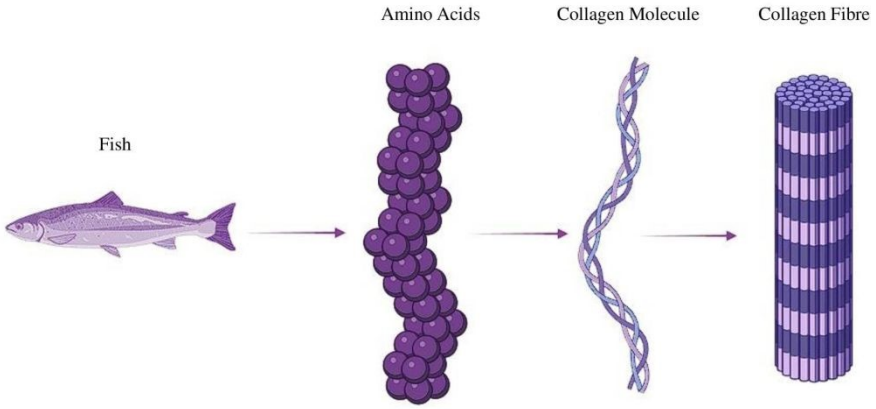

Fig.3. Collagen formation from Fish source

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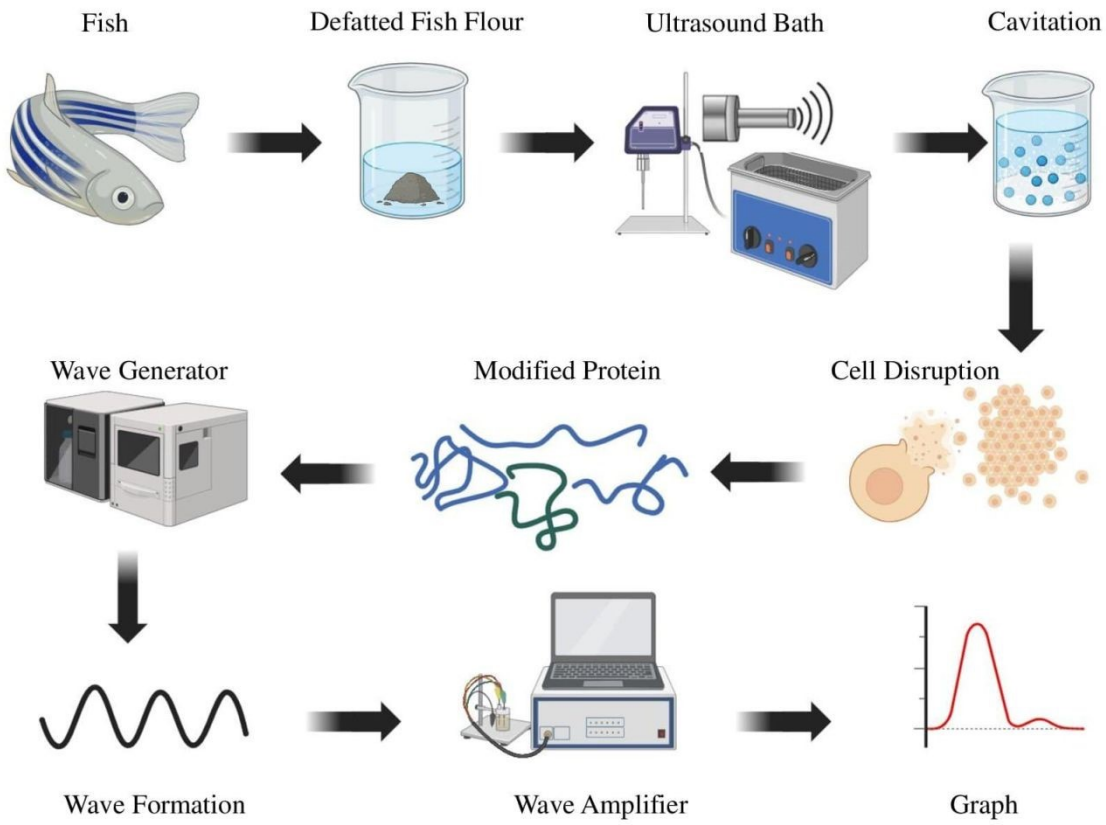

Fig.4. Protein extraction using ultrasound treatment

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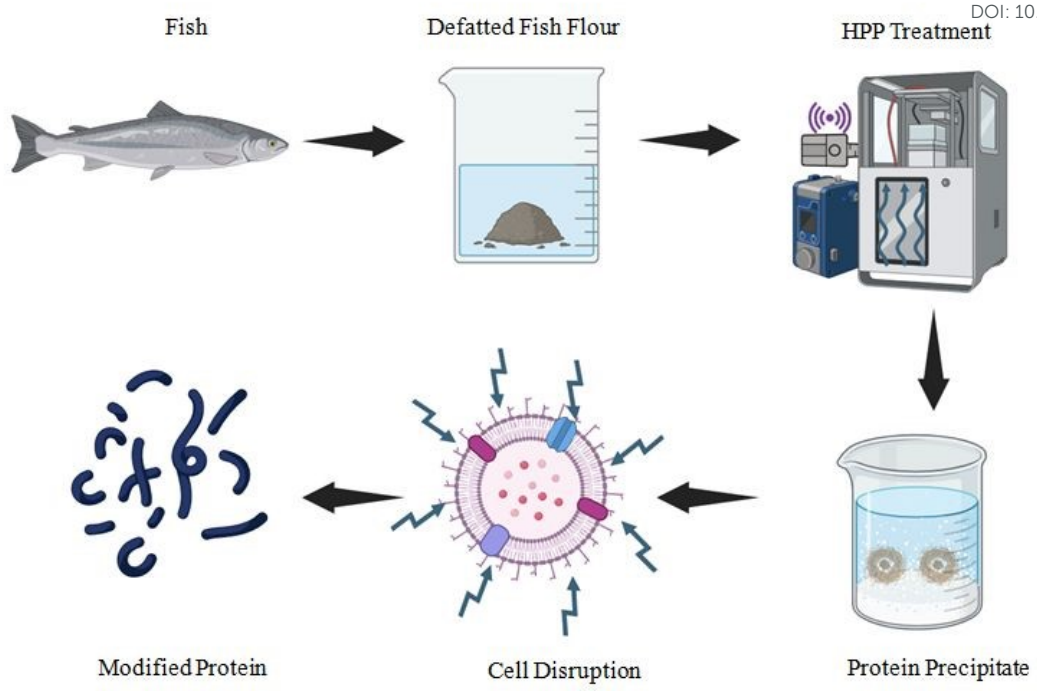

Fig.5. Cell disruption in protein molecule using HPP treatment

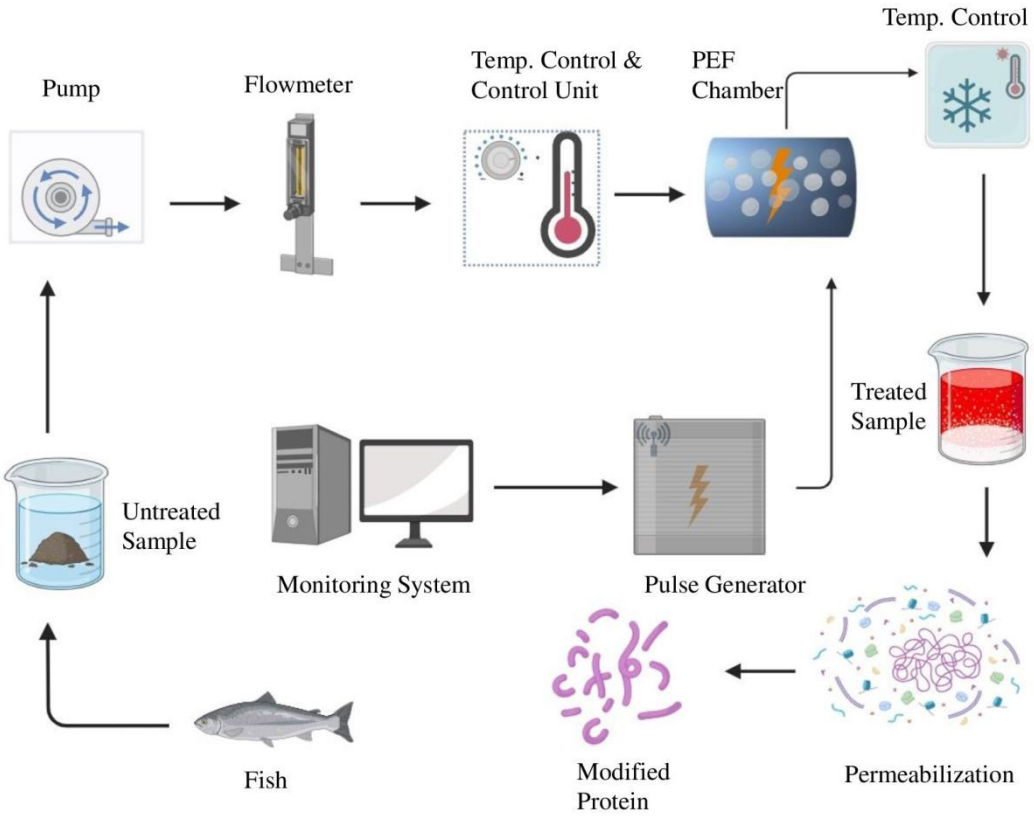

Fig.6. Cell permeabilization in protein for pulsed electric field

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Data Availability Statement

Data sharing does not apply to this article as no new data were created or analyzed in this study. The manuscript is based entirely on published literature that is appropriately cited and available in the public domain.