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Blue food proteins: Novel extraction technologies, properties, bioactivities and applications in foods

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ABSTRACT

With the growing demand for healthy and sustainable food, blue food proteins have emerged as an important way to address resource-intensive production and environmental concerns. This paper systematically reviewed the extraction technologies, properties and bioactivities of blue food proteins and explored their wide range of applications. The novel extraction technologies not only improve the extraction efficiency of the proteins, shorten the production time and have environmental advantages, but also enhance the protein properties and facilitate subsequent applications. The amino acid composition of the blue food proteins is close to the FAO recommended standard and better than most of the livestock proteins, with excellent solubility and water holding capacity. Some of the proteins also have significant bioactivity and show great potential for improving health. Applications include emulsions, protein films, microcapsules, food colorants, dietary supplements, 3D printing materials, and cultured meat. This paper provides theoretical support for further research and application of blue food proteins and promotes their wider application in future food products.

1. Introduction

Blue food, also known as aquatic food, originates from aquatic ecosystems and encompasses animals, plants and algae (Fig. 1) (Xu et al., 2022). The aquatic system, which occupies about 71% of the Earth's surface area, provides a vast living space for blue food resources. Currently, 624 species or species types are farmed in captivity, capturing more than 2370 taxa (Golden et al., 2021). In 2022, total global blue food production had reached 223.2 million tons, contributing trillions of dollars to the world economy (FAO, 2024). It can be seen that blue food is an important means of reducing global hunger, providing nutrients and supporting livelihoods, economies and cultures around the world.

Conventional food production imposes significant environmental pressures, accounting for about a quarter of global greenhouse gas emissions and consuming large amounts of land and water resources (Ritchie and Roser, 2024), and even so, many people around the world are still starving. The development of blue foods could improve these problems. Compared to land-based food production, blue food systems are relatively environmentally sustainable and typically generate lower environmental stress (Bank et al., 2022). In particular, some blue food production systems that do not require additional feeding, such as seaweeds and bivalves, also clean the environment by absorbing nutrients from the water (Crona et al., 2023).

Blue foods are rich in protein, and provide an important source of protein for more than 3.2 billion people worldwide (Brien et al., 2022; Golden et al., 2021). Blue food proteins are diverse and can be categorized into three main groups: water-soluble, salt-soluble and insoluble proteins (Nurdiani et al., 2020). Sarcoplasmic proteins are water-soluble proteins, including proteolytic enzymes and myoglobin (Nurdiani et al., 2020; Vieira et al., 2018). Myofibrillar proteins are known as salt-soluble proteins, including myosin and actin (He et al., 2022; Nurdiani et al., 2020). The muscles of invertebrate blue foods (such as

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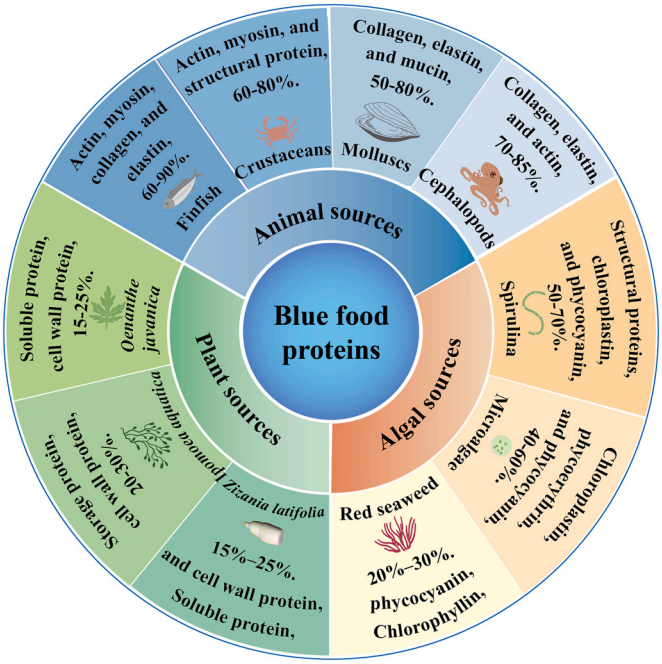

Fig. 1. Sources of blue food proteins and their content (in dry weight). Aquatic animal sources: finfish (60–90%), crustaceans (60–80%), cephalopods (70–85%), molluscs (50–80%), etc. Aquatic plant sources: *Oenanthe javanica* (15–25%), *Ipomoea aquatica* (20–30%), *Zizania latifolia* (15–25%), etc. Aquatic algal sources: red seaweed (20–30%), spirulina (50–70%), microalgae (40–60%), etc. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

scallops, squid, and oysters) contain paramyosin, which is not present in vertebrate blue foods (Vercruysse et al., 2005). Stromal proteins are insoluble proteins, including collagen, elastin and proteoglycan, among which collagen is the main component (Nurdiani et al., 2020). In addition, blue food proteins are of high quality and offer advantages over terrestrial animal proteins in terms of their comprehensive amino acid composition, unique flavor, cost-effectiveness, ease of digestion, and freedom from religious restrictions (Han et al., 2022). Blue foods will play an important role in the transformation of the food system as the future global population growth leads to increased protein and food demand.

At present, traditional methods such as water extraction, acid and alkaline solution extraction, and organic solvent extraction are usually used to extract proteins from blue foods. Although these technologies are mature, they suffer from the deficiencies of high solvent consumption, time-consuming, and low extraction rate. With the in-depth research on the utilization of blue food protein resources, how to efficiently extract and utilize its rich protein resources has become the focus of researchers' attention. In particular, the extraction and utilization of blue food proteins can not only help to meet the challenge of global protein supply, but also satisfy the increasing demand for functional foods. In this context, this paper mainly reviews the novel extraction methods of blue food proteins, including pulsed electric field extraction, microwave-assisted extraction, ultrasound-assisted extraction, steam explosion extraction, pressurized liquid extraction, and liquid biphasic electric flotation extraction; summarizes the nutritional properties, functional properties, and bioactivities of blue food proteins. In addition, the routine applications of blue food proteins and their applications in future foods are also introduced.

2. The latest advances in blue food protein extraction technology

The traditional technologies of protein extraction have the disadvantages of low yield and long time, so more and more new extraction technologies and new auxiliary extraction technologies are designed to improve the yield and efficiency. The perfect protein extraction technology should be easy to operate, efficient and environmentally friendly, while maintaining the quality of the protein. Several novel protein extraction technologies are discussed below (Raja et al., 2022), some of which are illustrated in Fig. 2.

2.1. Thermal extraction

2.1.1. Microwave-assisted extraction

Microwave-assisted extraction (MAE) is a technology in which the system absorbs microwaves and then transfers the energy to the solvent after converting it into heat through ionic conduction and dipole rotation (Guo et al., 2024). After microwaves are applied to the extraction system, the microwaves cause water molecules and other polar molecules to vibrate, these molecules rub and collide with each other, thus generating heat, the temperature of the liquid inside the cell rises, which further causes the water to evaporate and the intracellular pressure to increase, which acts on the cell membranes, and ultimately results in the rupture of the cell (Kapoore et al., 2018; Zhang et al., 2011). This process effectively achieves the destruction of the cell structure, creating conditions for the release of the target protein, and is therefore particularly advantageous when dealing with complex biological samples. In addition, microwaves promote the movement of dissolved ions and the breaking of hydrogen bonds, increasing the penetration of solvent into the sample, which in turn greatly reduces the amount of solvent used, shortens the time of action, and improves the extraction rate (Kadam et al., 2013; Kapoore et al., 2018). MAE is an environmentally friendly, efficient, simple protein extraction technology, and the extraction effect is related to the microwave's power, duty cycle and duration of the microwave, and the temperature of the system (Brien et al., 2022). In addition, the dielectric constant of the sample and the solvent are also important influencing factors, the higher the dielectric constant, higher dielectric constant leads faster energy conversion, with a consequent increase in temperature and extraction efficiency (Rostagno et al., 2009). Chew et al. (2019) developed an effective and environmentally friendly microwave-assisted three-phase partitioning (ammonium sulfate solution, microalgae slurry, and tert-butanol) method, which, under optimal conditions (ammonium sulfate concentration of 30%, the volume ratio of tert-butanol to slurry was 1:1, microwave treatment at a power of 100 W for 120 s, and with a duty cycle of 80%), resulted in the recovery of 63.2% of the microalgae protein, the recovery was increased by 2.54 times. Vali Aftari et al. (2015) used ultrasound-assisted extraction technology and MAE technology, respectively, to obtain C-Phycocyanin from *Spirulina platensis*, and under the optimal conditions, it was found that the MAE technology (pH 7.0, 25 min) was more favorable for extracting C-Phycocyanin of higher concentration and purity, and it was possible to achieve a C-Phycocyanin extract with a concentration of 4.54 mg/mL, which is better than the results of some other researchers. The results showed that the MAE technology is beneficial to extract C-Phycocyanin of higher quality from *Spirulina platensis*. However, the equipment for MAE is more expensive and is based on microwave heating, which is deficient in the extraction of heat-sensitive substances.

Overall, MAE shows great potential as an efficient and environmentally friendly technology. However, the optimization of parameters for specific protein types and target products, especially for the protection of heat-sensitive substances, still needs to be further explored.

2.1.2. Pressurized liquid extraction

Pressurized liquid extraction (PLE) is a technology that uses critical high temperature (50–200 °C) and high pressure (35–200 bar) to

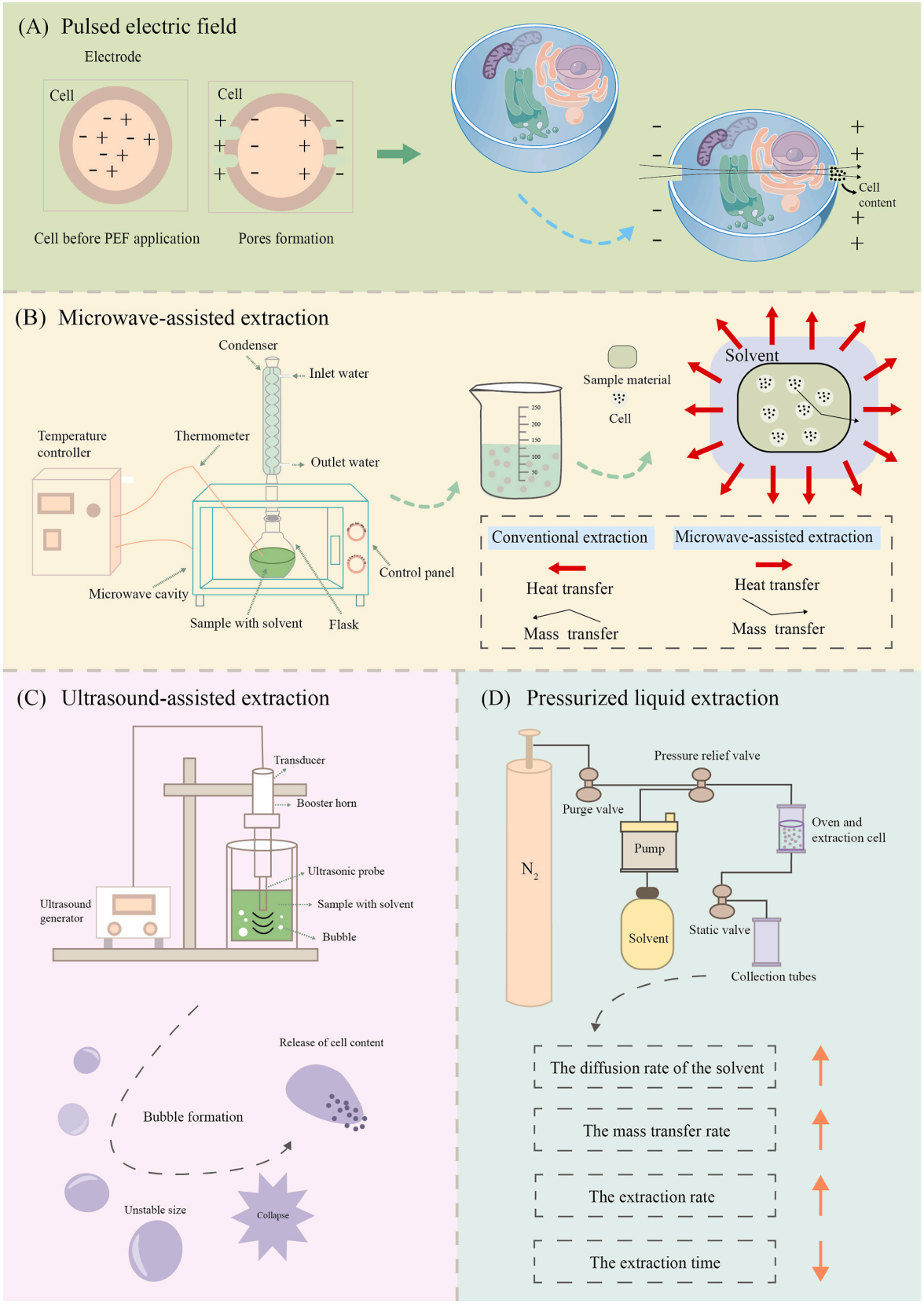

Fig. 2. Part of novel extraction technologies for blue food proteins. (A) Pulsed electric field. (B) Microwave-assisted extraction. (C) Ultrasound-assisted extraction. (D) Pressurized liquid extraction. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

improve the diffusion rate of the solvent, mass transfer rate and the solubility of the target substance, thereby improving the extraction rate and shortening the extraction time, also known as accelerated solvent extraction, pressurized hot solvent extraction, etc. (Gordalina et al., 2021). High temperature and high pressure ensure the high efficiency of PLE. The use of non-toxic extraction solvents ensures that PLE is safe and environmentally friendly (Ganjeh et al., 2023). Automation and the ability to process multiple samples simultaneously make PLE faster and use less solvent (Zhou et al., 2021). These advantages have made the technology increasingly popular for extracting compounds from food products. PLE can be categorized into static and dynamic modes. Keeping the temperature and pressure constant and setting your own extraction time as needed is the static mode. The mode in which the extractant (water in most cases) is continuously flowing through the sample is known as the dynamic mode, which produces a voluminous extract that is not conducive to the purification of the target extract. A combination of the two modes can be used to achieve better extraction results (Carabias-Martínez et al., 2005; Perez-Vazquez et al., 2023). Temperature, extractant, pressure, duration, number of extractions and sample size are factors that affect the extraction effect and need to be set reasonably (Nieto et al., 2010). de la Fuente et al. (2021) used PLE (water as extractant) to extract proteins from sea bass (*Dicentrarchus labrax*) muscle, head, viscera, skin, and tailfin, respectively, under their respective optimal extraction condition, protein content and antioxidant capacity were increased by 1.2–4.5 times and 1–5 times, respectively, compared to conventional extraction. Zhou et al. (2021) used PLE to gain nutrients and active compounds from spirulina, the results showed that the extraction rate of protein was 46.8 ± 3.1%, which was significantly improved.

In summary, PLE shows great application prospects for the efficient extraction of proteins and active compounds. Although its high temperature and pressure conditions require higher equipment costs and maintenance, it has advantages that cannot be ignored in terms of efficiency, safety and environmental protection. With the gradual reduction of equipment costs and further optimization of technology, PLE is expected to be more widely used in food processing, biopharmaceutical and functional food development.

2.1.3. Steam explosion

Steam explosion is a novel extraction technology involving a physicochemical process. The sample is treated with a short period of saturated steam pressure (150–210 °C, 0.5–2.0 MPa), followed by an instantaneous reduction in pressure (i.e., steam explosion, within 0.00875 s) and a simultaneous cooling to 50 °C or lower (Dong et al., 2021; Guo et al., 2020). This technology has the advantages of short duration, low cost, low reagent usage, and less pollution. Dong et al. (2021) extracted proteins from fish backbones by two methods: steam explosion-assisted extraction after heat treatment (159 °C water, 2 min) and extraction by heat treatment (121 °C water, 70 min). The results showed that the protein content could reach 81.09–84.88 g/100 g. After enzymatic hydrolysis, the degree of hydrolysis and nitrogen recovery in the steam explosion treatment group was higher. This indicates that steam explosion is favorable for protein extraction and its hydrolysis.

Steam explosion can preserve the structure and function of proteins to a great extent by instantaneous depressurization and cooling, reducing degradation or denaturation caused by excessive heating. However, although the steam explosion technology shows significant advantages in protein extraction, further optimization of the steam parameters and the pressure reduction process remains a focus of future research. Different biological matrices have different sensitivities to the treatment conditions and therefore need to be adapted to the specific protein source in practical applications.

2.2. Non-thermal extraction

2.2.1. Pulsed electric field

Pulsed electric field (PEF) extraction is a new type of technology based on electric energy development, with low energy consumption, continuous operation, short time consuming, environmentally friendly and other advantages, and non-thermal technology, which can guarantee good quality of protein, and is a hot field in food research (Gómez et al., 2019). Between the positive and negative electrodes, blue foods are positioned, so that each charge produces a short pulse of high-voltage current. The appropriate high-voltage current pulse can hit through the cell membrane, increase the original holes on the membrane and produce new holes, and the proteins in the cell will leak from the holes to achieve the purpose of improving the yield (Gordalina et al., 2021; Pliego-Cortés et al., 2020). The efficiency of protein extraction by PEF is affected by many factors, such as the pulse intensity, pulse frequency, number of pulses and duration, the appropriate high-voltage current pulse will produce irreversible electroporation on the cell membrane, which is particularly important for protein extraction (Gómez et al., 2019; Gordalina et al., 2021). Therefore, appropriate PEF process parameters need to be set according to cell characteristics and requirements. Using freshwater mussels as raw materials, Zhou et al. (2017) designed the experiment using the response surface method, and combined with the operating cost, obtained the optimal PEF process parameters: the pulse intensity is 20 kV/cm, the pulse number is 8, and the pulse frequency is 40–3000 Hz, pulse duration of 2 μs, and enzymatic hydrolysis time is 2 h. In these cases, the protein extraction rate can reach 77.08%, which is 4.13, 1.05 and 1.18 times of sodium chloride method, alkali method and enzymatic method (traditional method), and the cost and time are reduced, which is a promising protein extraction technology. This result shows that the PEF technology not only significantly improves the protein extraction rate, but also has significant advantages in terms of cost and time, indicating its economic feasibility in production. The viscera is a by-product of abalone, accounting for 20–30% of the weight of abalone, and directly discarding it not only pollutes the environment, but also a huge waste (Li et al., 2016). Li et al. (2016) extracted abalone viscera protein by PEF-assisted enzyme method. The effects of different pulse intensities, durations and material-to-solvent ratios on the experiment were studied. The results indicated that when the pulse intensity was 20 kV/cm, the duration was 600 μs, the material-to-solvent ratio was 4:1, had the highest protein extraction rate. Moreover, compared with enzymatic extraction alone, PEF can optimize the solubility and emulsifying property of abalone viscera protein to a certain extent, and reduce the viscosity. There are some shortcomings in applying PEF to the food field. For example, putting food between the positive and negative electrodes generates a high-voltage current pulse, which limits the space in the treatment room and reduces the processing capacity (Niu et al., 2020). In addition, PEF may cause changes in protein conformation, which in turn leads to changes in biological activity.

In summary, PEF technology is advantageous because of its high efficiency, non-thermal, and environmentally friendly properties, and shows significant potential for maintaining protein functionality in particular. However, to achieve a wide range of applications, operational parameters need to be optimized for specific substrate and product targets, and potential challenges posed by spatial constraints and protein conformational changes need to be addressed.

2.2.2. Ultrasound-assisted extraction

Ultrasound is a mechanical wave that cannot be perceived by the human ear and has a frequency higher than 20 kHz, which can be divided into high frequency (frequency >100 kHz) and low frequency (frequency range 20–100 kHz), the latter is usually used for ultrasound-assisted extraction (UAE) (Flores-Jiménez et al., 2023). Ultrasound can increase the extraction rate of protein mainly based on the cavitation effect produced by ultrasound, and the resulting mechanical effects (Han

et al., 2022). Specifically, ultrasound in the form of longitudinal wave propagation in the extraction system, the process will make the solvent periodic stretching and compression, due to continuous dilution and compression, so that the uniform solvent produces a pressure difference (the solvent is diluted by the solvent pressure is small, the solvent compressed by the solvent pressure is large), in the pressure difference under the impetus and the rapid flow of the solvent, when the solvent's hydrostatic pressure is lower than the saturation vapor pressure, the solvent evaporation and the production of steam bubbles, this time known as the stability of the cavitation (Batghare et al., 2020; Deng et al., 2022). Bubbles in the action of ultrasound, continue to generate, growth and aggregation, at a certain point, the bubble's bearing capacity reaches the limit and ruptures (at this time can be called transient cavitation), resulting in shock waves, local extreme pressure and temperature and other secondary phenomena, periodic bubble bursting produces periodic secondary phenomena, ultimately leading to the rupture of the cells or tissues, to accelerate the extractant into the cells and the outflow of the cellular contents (Chemat et al., 2017; Deng et al., 2022; Wen et al., 2018). This cavitation effect can dramatically increase extraction efficiency, and is particularly effective against cell rupture when treating raw materials with dense structures and hard cell walls (algae, for example, usually have thick cell walls that contain tough components such as cellulose and polysaccharides). The proteins in fish and crustaceans are distributed in the muscle tissue or outer layer of the shell. The action of ultrasound is effective in disrupting the structure of these tissues, increasing the rate of water penetration and solubilization, and allowing for a more rapid release of proteins. Compared with traditional extraction technology, UAE consumes less solvent, saves time and can be used to extract heat-sensitive substances (Chemat et al., 2017). Various factors such as the frequency, intensity and power of the ultrasound waves, the shape and size of the reaction vessel, and the extraction solvent used can influence the cavitation effect and the final protein extraction effect (Chemat et al., 2017). Therefore, it is crucial to optimize these parameters in industrial applications to ensure optimal extraction efficiency and quality. Heidari and Rezaei (2022) extracted pepsin from rainbow trout stomachs and used these enzymes to extract pepsin-soluble collagen from yellowfin tuna skin. Ultrasonic treatment for 15 min increased the collagen extraction rate from 18.56% to 23.84% and improved the viscosity and antioxidant capacity of the collagen as well as giving good water holding capacity, emulsification and solubility in acidic environments as compared to the extraction technique without the application of ultrasound. Lian et al. (2021) used simultaneous dual-frequency divergent UAE of *Chlorella pyrenoidosa* protein, and under optimal conditions, the extraction of *Chlorella pyrenoidosa* protein could reach 52.36%, compared with hot water extraction, it has been significantly improved, and it proved that ultrasound-assisted was a time-saving and efficient protein extraction method.

Overall, UAE technology shows a broad application prospect in the field of blue food protein extraction due to its high efficiency, energy saving, environmental protection and protection against heat-sensitive substances. With the further maturation and optimization of the technology, its potential for application on an industrial scale will become more and more prominent.

2.2.3. Liquid biphasic electric flotation

Liquid biphasic electric flotation is an efficient protein extraction method that combines electrolysis and liquid biphasic flotation (Sankaran et al., 2018). Currently, it is mainly used for microalgae protein extraction within the blue foods range. Electrolysis can disrupt the cell membrane of microalgae and increase its permeability, which is favorable for protein extraction (Sankaran et al., 2018). Combined aqueous two-phase systems and solvent sublation are two components of liquid biphasic flotation used to separate and extract proteins (Koyande et al., 2019; Sankaran et al., 2018). Sankaran et al. (2018) extracted *Chlorella sorokiniana* CY-1 proteins under optimal conditions (60% (v/v) of 1-propanol in the top phase, 250 g/L of dipotassium hydrogen phosphate in the bottom phase, 0.1 g of crude microalgae uptake, 150 cc/min air flow rate, 10 min flotation time, 20 V voltage, and electrode tip contacting the liquid biphasic electric flotation top phase), and separation efficiency and protein recovery of 173.0870 ± 4.4752% and 23.4106 ± 1.2514%, both of which were improved compared to liquid biphasic flotation alone. Similarly, Koyande et al. (2019) used liquid biphasic electric flotation to extract protein from *Chlorella Vulgaris*, which also improved the extraction and recovery rates of protein.

Novel protein extraction technologies each have their characteristics and are adapted to different extraction needs. MAE technology can effectively improve extraction efficiency and reduce the use of solvents by rapidly heating the substance. However, this method may lead to the degradation of heat-sensitive proteins and has some limitations in industrial-scale applications. PLE accelerates the extraction process under high temperature and pressure, which is widely applicable, but the equipment cost is high and the operation is complicated, requiring precise control of extraction conditions. Steam explosion technology through high-temperature steam to destroy the cell wall, promotes the release of proteins, and can reduce the use of chemical solvents, but energy consumption and may have an impact on the protein structure. PEF utilizes electric field pulses to treat samples, which can effectively maintain the functionality of proteins and is suitable for processing heat-sensitive proteins, but the equipment is expensive and the processing capacity is limited. UAE improves extraction efficiency through bubble bursting triggered by sound waves and is suitable for heat-sensitive proteins, but has limited efficiency for large-scale processing and high equipment and operating costs. Liquid biphasic electric flotation combines electrolysis and liquid biphasic flotation with high selectivity and is suitable for protein extraction in complex systems, but the technology is relatively novel, the equipment is complex, and the industrial application is still under development. Therefore, when choosing a suitable extraction technology, it is necessary to comprehensively consider factors such as the property of the protein, the purpose of extraction and the economy.

3. Properties of blue food proteins

3.1. Nutritional properties of blue food proteins

Digestibility and amino acid composition determine the nutritional value of proteins (Bleakley and Hayes, 2017). According to research, protein digestibility can reach 90% for most seafood and 75% for most algae (Raja et al., 2022; Sasidharan and Venugopal, 2020). The FAO and the WHO have stipulated that the content of essential amino acids in high-quality food proteins must be more than 40%, and the ratio of non-essential amino acids to essential amino acids must be more than or equal to 0.60 (Elgaoud et al., 2023). Different types of blue foods have different amino acid types and contents. In general, blue food proteins conform to the above indicators and have amino acid scores close to the FAO recommendations, and are high-quality sources of protein.

Between the different types of blue foods, amino acid differences further enrich their nutritional diversity. Crustaceans usually have a higher amino acid content compared to fish, and the abundance of arginine, glutamic acid, glycine and alanine gives them a unique nutritional value (Nurdiani et al., 2020). It should be noted in particular that animal blue food proteins are rich in lysine and methionine, two amino acids that are relatively lacking in plant proteins, therefore, it has an important complementary effect on the diet structure of plant protein deficiency (Tacon and Metian, 2013). However, seaweed foods exhibit a unique amino acid composition. In addition to lysine and methionine, seaweeds are rich in phenylalanine, tyrosine, and threonine, which are all essential amino acids (Raja et al., 2022). In addition, the abundance of non-essential amino acids (glutamic acid and aspartic acid) gives seaweed its unique flavor (Lourenço et al., 2002). This property suggests that seaweed proteins are not only a good source of dietary amino acids,

but also have the potential to be used as ingredients in flavored and functional foods. Blue food proteins also showed a clear advantage in terms of protein efficacy ratio. Protein efficacy ratio (the number of grams of body weight gained from an average intake of 1 g of protein) is an indicator of protein utilization, and seafood's protein efficacy ratio ranges from 3.1 to 3.7, which is higher than that of most livestock and poultry proteins (Sasidharan and Venugopal, 2020). In addition, animal blue foods are much lower in collagen, which is more beneficial to human health when ingested. These factors further support the superiority of blue food proteins in the diet, making them not only an efficient source of protein, but also a key component of a healthy diet (Weichselbaum et al., 2013). Through the analysis of specific blue foods, their potential for nutritional supplementation was further confirmed. Abdollahi and Undeland (2018) extracted isolate proteins from salmon, cod, and herring by-products and dried them into protein powders with essential amino acids well above the recommended requirements for adults. The lysine content can reach 91–101 mg/g, which is higher than the reference proteins soy isolate (72 mg/g) and egg white protein (81 mg/g), and can compensate for lysine deficiencies in some grain proteins.

In summary, blue food proteins not only exhibit excellent digestibility and amino acid composition, but their unique amino acid profiles and higher protein efficiency ratios make them irreplaceable in nutritional supplementation and health promotion. These characteristics position blue food proteins with significant potential in future food science research and applications, especially in addressing global protein shortages and improving dietary quality.

3.2. Functional properties of blue food proteins

Functional properties of proteins refer to the physicochemical properties of proteins that are beneficial to food, mainly including solubility, emulsifying property, film-forming property, gelling property, water holding capacity and oil holding capacity (Khan et al., 2022).

3.2.1. Solubility

Solubility is considered to be a fundamental functional property of proteins, which affects other functional properties such as emulsifying property and foaming property, and largely determines the suitability of the protein for use in food products, and usually, proteins with good solubility are the ones that meet the requirements of food production (Małecki et al., 2021). Surface hydrophobicity and charge are the main reasons for the solubility size of proteins; hydrophobicity promotes interactions between proteins and maintains the protein's conformation, thus decreasing solubility, while charge promotes the interaction of proteins with the solvent water, which can increase solubility (Khan et al., 2022; O'Brien et al., 2007). In addition, some other conditions such as temperature, solvent type, pH, and ionic strength also have an effect on protein solubility, especially pH (Małecki et al., 2021). Changes in pH affect the net charge of proteins, which in turn changes the electrostatic repulsion between protein molecules, increasing or decreasing solubility, which is precisely why most proteins have the least solubility at the isoelectric point. At the isoelectric point, the electrostatic charge is 0, the electrostatic repulsion between proteins is minimized, and proteins are more likely to aggregate and lead to precipitation (Timilsena et al., 2016). The solubility of blue food proteins is similar to other proteins in that its solubility is lower at the isoelectric point and increased at pH away from the isoelectric point. Isolated proteins extracted from salmon and cod showed solubility of 9–11% near the pH corresponding to the isoelectric point, and when adjusted to pH $>$ 12, the solubility could reach more than 95%, showing better solubility than soybean protein isolate, providing a new option for the application of blue food proteins in food (Abdollahi and Undeland, 2018), this also indicates that blue food proteins have strong adaptability to processing. Carp proteins were extracted under acidic and alkaline conditions and the solubility could reach 66.67% and 62.08%, respectively (Tian et al., 2017). The solubility of algal proteins varied considerably, but in general, they also had high solubility. In addition, the treatment of blue food proteins with enzymatic hydrolysis (Elgaoud et al., 2023), high-pressure homogenization (Liu et al., 2021), and ultrasound (Purdi et al., 2023) under suitable parameters significantly improved their solubility. These technologies provide more options for the diverse applications of blue food proteins in the food industry.

3.2.2. Water holding capacity and oil holding capacity

Water holding capacity is the ability of proteins to retain water in their tissues and can be of great practical importance as it affects the tenderness, juiciness, mechanical strength and plasticity of certain foods. The amino acid composition, conformation and various polar groups on the surface of proteins are considered to be internal factors affecting water holding capacity; pH, ionic strength and the presence of other components are extrinsic factors (Rawiwan et al., 2022). Proteins from fish muscle have good water holding capacity (Sasidharan and Venugopal, 2020). Whereas the water holding capacity of seaweed proteins is less studied, existing studies have revealed their potential water retention. For example, the protein concentrate of *Kappaphycus alvarezii* had a water holding capacity of 2.22 $\pm$ 0.04 g H_2O/g protein according to Suresh Kumar et al. (2014). The water holding capacity of blue food proteins can be further enhanced by a variety of processing methods, such as enzymatic hydrolysis, washing and other measures (Elgaoud et al., 2023; Sasidharan and Venugopal, 2020).

Oil holding capacity is produced by hydrophobic interactions between the nonpolar groups of proteins and the lipid hydrocarbon chains, which can not only improve the sensory properties, but also extend the shelf life of food, and has a wide range of application values (Elgaoud et al., 2023). The oil holding capacity of scallop gonadal isolates extracted by Han et al. (2019) was 5.2 mL/g. The oil holding capacity of *Chlorella pyrenoidosa*, *Arthospira platensis* and *Nannochloropsis oceanica* proteins extracted by Chen et al. (2019) was 6.68 $\pm$ 0.41, 8.37 $\pm$ 1.45, 8.25 $\pm$ 0.44 g oil/g protein, which was significantly higher than that of soybean protein isolate (3.9 mL/g).

In summary, blue food proteins show a wide range of applications in terms of water and oil holding capacity.

3.2.3. Gelling property

Gelation is important for some food products, such as fish balls and some other fish products. Gelation is not just a physical change, it involves complex chemical interactions between protein molecules and is one of the manifestations of the functional properties of proteins. In the process of gelation, the interactions between protein molecules are increased by several methods, which firstly lead to a change in protein conformation or partial extension, and once the cross-linking between molecules can be formed into a continuous, reticulated structure capable of holding substances such as water, a gel system will be formed (Foegeding and Davis, 2011; Sasidharan and Venugopal, 2020). In most cases, heat treatment is necessary for the formation of gels from proteins (denaturation and unfolding of proteins), followed by the formation of stable gels through hydrogen bonding between peptide chains upon cooling. In addition, many non-thermal means can also lead to gel formation, such as pH adjustment, addition of divalent metal ions and appropriate enzymatic digestion. Sánchez-Alonso et al. (2007) obtained giant squid (*Dosidicus gigas*) protein gels with a gel strength of about 400 g/cm^2 at 90 °C, 0.2% $Ca(OH)_2$ and 1% NaCl. This result shows that blue food protein can form a gel with high mechanical strength under high temperature and appropriate ionic environment. The key chemical interactions during gelation are mainly maintained by hydrophobic interactions and disulfide bonds, these chemical bonds give protein gels excellent stability and viscoelasticity, which is demonstrated in some blue food proteins. For example, these chemical bonds confer better viscoelasticity to bighead carp (*Aristichthys nobilis*) protein gels (Chang et al., 2015). Edible blue-green algae (*Spirulina platensis* strain pacifica) protein isolates also exhibited excellent gel properties (Chronakis,

2001).

3.2.4. Emulsifying property

An emulsion is a dispersion system consisting of two or more insoluble liquids. The liquids are insoluble with each other, so emulsions are unstable and their stability needs to be improved in food production (Małecki et al., 2021). Emulsion stability is crucial for the shelf life and texture of food products, so how to utilize natural ingredients to enhance the stability of emulsions is one of the important research topics in food science. Proteins are amphiphilic and are natural emulsifiers (Luo and Wei, 2023). After soluble proteins are added to the emulsion system, the hydrophobic amino acids are aligned to the non-aqueous phase, which reduces the free energy of the system, and the other parts of the protein are stretched and adsorbed at the interface between the dispersed phase and the continuous phase, and the higher the concentration of adsorbed protein, the smaller the interfacial tension, and the more stable the system will be (McClements and Jafari, 2018). The time required to stabilize an emulsion is related to the structure of the protein. Proteins with a stable, compact structure are not suitable or take longer to stabilize an emulsion system. Proteins with a loose structure can stabilize the system more quickly (Małecki et al., 2021). This suggests that protein selection and pretreatment processes are critical in emulsification applications, and that loosely structured proteins may have greater potential for application in the food industry due to their fast adsorption and dispersion properties. EAI and ESI characterize the ability of proteins to form and stabilize emulsions, respectively; the higher the EAI and ESI values, the better the emulsification capability (Purdi et al., 2023). Table 1 summarizes the emulsifying ability and mechanism of some blue food proteins.

Fish proteins have good emulsifying properties. Abdollahi and Undeland (2018) studied salmon, cod, and herring proteins, which had similar emulsification capabilities to soy proteins, with cod proteins having better emulsification capabilities because of their higher surface hydrophobicity and myosin heavy chain content. The excellent emulsifying ability of cod protein further supports the potential application of blue food protein in emulsified foods, especially in the development of processed and functional foods. In addition, Yoon et al. (2019) extracted isolated proteins from yellowfin tuna roe with slightly higher emulsification capacity than casein (7.0 m^2/g), which could reach 10.0 m^2/g, also demonstrating the potential of blue food protein in high-performance emulsifiers.

Suresh Kumar et al. (2014) studied the emulsification capability of protein concentrate of *Kappaphycus alvarezii* in various oil-water systems and found that it has good emulsification capability for groundnut, cotton seed and olive oils. The researchers concluded that the hydrophobic component was responsible for the formation of stable emulsions. Ultrasound-assisted (Purdi et al., 2023), succinylation (Krasaechol et al., 2008) improves the emulsifying properties of blue food proteins, these technologies provide the food industry with effective means to enhance the applicability and stability of blue food proteins in complex emulsion systems.

In summary, the emulsifying ability of blue food proteins showed significant advantages, and with the increasing demand for natural emulsifiers in the food industry, blue food proteins will play a more important role as potential emulsifiers in future food production.

3.2.5. Foaming property

Foam is usually a dispersion system in which air bubbles are dispersed in a continuous liquid phase or semi-solid containing surfactant (Foegeding and Davis, 2011). Proteins are amphiphilic and can easily migrate, adsorb to, and rearrange at interfaces. Hydrophilic amino acids on the surface of proteins arrange themselves in the liquid, and hydrophobic amino acids arrange themselves in the air, which reduces the interfacial tension, thus forming and stabilizing foams (Małecki et al., 2021). Foaming capacity and foam stability are two indicators for evaluating foaming properties (Rawiwan et al., 2022). Foaming capacity refers to the amount of foam generated at the start of churning, which is usually affected by the type, molecular structure and concentration of the surfactant, while foam stability refers to the length of time the foam exists (Elgaoud et al., 2023). Suresh Kumar et al. (2014) found that the foaming property of *Kappaphycus alvarezii* protein concentrate was related to pH, with the highest foaming capacity (53.33 ± 2.31%) at pH 4.0, and the highest foaming stability (45.33 ± 1.15%) was recorded after 30 min at pH 2.0. Garcia-Vaquero et al. (2017) extracted proteins from the brown seaweed *Himanthalia elongata* (Linnaeus) S. F. Gray with a foaming capacity of 71.52 ± 4.81% at pH 10.0.

Overall, the foaming properties of blue food proteins are influenced by multiple factors such as their molecular structure and environmental conditions. By optimizing these conditions, blue food proteins have great potential for use as natural foaming agents in the food industry.

3.3. Bioactivities of blue food proteins

Some blue food proteins are found with some biological actives and may provide some reference for functional foods and drug development.

Heavy metal ions can enter the body with food and circulate throughout the body with the blood, causing damage to several systems of the human body, resulting in a variety of diseases such as dizziness,

Table 1
Emulsifying ability and mechanism analysis of some blue food proteins.

No.	Protein sources	Experimental conditions	EAI (m^2/g) and ESI (min)	Mechanisms	References
1	Cod	pH 11.0	64; /	Higher surface hydrophobicity and myosin heavy chain content	Abdollahi and Undeland (2018)
2	*Spirulina platensis*	Ultrasound assisted extraction	130.50 ± 2.91; 98.17 ± 1.15	It is possible that ultrasound leads to a conformational change in the protein, which improves the ESI	Purdi et al. (2023)
3	Mussel myofibrillar proteins	High intensity ultrasonication treatment	33; 78	Ultrasound leads to an increase in protein surface hydrophobicity and a decrease in particle size	Yu et al. (2022a)
4	Yellowfin tuna roe	pH 10.0	31.1; 49.4	/	Yoon et al. (2019)
5	Threadfin bream sarcoplasmic protein	Succinylation	145; 160	Succinylation increases protein solubility and amphiphilicity	Krasaechol et al. (2008)
6	Golden pompano	pH 3.0	42; 92	Carrying more net charge, easier to distribute proteins evenly	Sun et al. (2022)
7	Sea cucumber guts	pH 8.0	224.85; 58	Under this condition, droplet aggregation can be effectively avoided, thus improving the stability of the emulsion	Du et al. (2019)
8	Scallop	High intensity ultrasonication treatment	13.1; 72	Ultrasonication leads to a change in protein conformation, an increase in surface hydrophobicity and a decrease in particle size	Yu et al. (2022b)
9	Sea bass	Ultrasonication treatment, low salt solution	About 100; about 120	Ultrasonication increases protein solubility and hydrophobicity	Lan et al. (2024)
10	*Pseudosciaena crocea roe*	Papain digestion	85.27; about 25	Enzymatic digestion produces more low molecular weight peptides that promote migration to the water/oil interface	Jin et al. (2024)
11	Scallop	High hydrostatic pressure	75.09; about 17	Increased protein hydrophobicity	Ding et al. (2022)

headache, joint pain, cancer, etc. and may also cause oxidative stress and denaturation of nucleic acids (Carolin et al., 2017). Ferritin is a cage-shaped protein composed of a dodecahedral protein shell and an iron core, of which the protein shell is in turn composed of 24 subunits (except *Listeria Innocua*), between which four-, three- and two-fold symmetrical channels are formed to ensure the entry and exit of substances (Li et al., 2022). According to the research, this protein has some advantages in removing heavy metal ions. Li et al. (2022) studied the heavy metal ion removing activity of oyster ferritin. The structure of oyster ferritin is stable, which can resist the denaturation caused by Pb^{2+}. Based on this, the existence of some amino acids and special structures enables ferritin to significantly bind heavy metal ions. The results of cell experiments and animal experiments also showed that ferritin can significantly reduce the content of Pb^{2+} and has a strong protective effect against the attack of heavy metal ions.

Senthilkumar and Jayanthi (2016) isolated and purified glycoprotein from green seaweed *Codium decorticatum* possessed anticancer activity and in this study, both MTT and LDH assays were consistent, suggesting that the glycoprotein can penetrate cancer cells (human breast (MCF 7), cervical (Siha) and lung (A549) cancer cells) leading to disruption of plasma membrane integrity, which in turn leads to apoptosis and LDH leakage. To provide a reference for protein-based anti-cancer drug development. However, the exact mechanism by which glycoprotein inhibits cancer cells remains to be investigated.

Patel et al. (2018) investigated the antioxidant activity of *Halomicronema* phycoerythrin. In this study, 2, 2-diphenyl-1-picrylhydrazyl (DPPH)-radical scavenging activity, ferric ion reducing ability of plasma (FRAP) assay and reducing power (RP) assay were used *in vitro* and *in vivo* experiments. The good antioxidant activity and anti-aging activity of phycoerythrin against *C. elegans* were verified. Amino acid sequencing and peptide mass fingerprinting revealed that a large number of residues and the chromophore PEB in phycoerythrin were the source of its antioxidant activity. It can contribute to the research of drugs for ROS-related diseases.

Phycocyanin is an important protein in spirulina, and it is difficult to find similar protein structures in terrestrial plants and animals, and has a variety of biological activities. The antidiabetic activity of phycocyanin was demonstrated in a study by Prabakaran et al. (2020), the results showed that the inhibitory activity of phycocyanin against α-amylase and β-glucosidase at a concentration of 250 μg/mL reached 72% and 65%, respectively, which was close to the inhibitory effect of acarbose (88% and 80%). Phycocyanin can also exert bioactivity to promote wound healing by promoting blood coagulation and fibroblast migration (Dev et al., 2020).

Arginine, glycine and taurine have been studied for their efficacy in reducing the release of pro-inflammatory factors, which play an important role in the recovery of skeletal muscle injuries. A study by Dort et al. (2012) found that cod protein, enriched in the above amino acids, could beneficially affect muscle recovery by decreasing the accumulation of neutrophils and ED24 macrophages, increasing the size of myofibrils, decreasing the expression of cytokines, such as TNF-α and IL-6, as well as better reversing bupivacaine-induced metabolic disorders in skeletal muscle to beneficially affect muscle recovery and promote muscle recovery. Fig. 3 summarizes some of the properties of blue food proteins.

Overall, these studies provide a solid foundation for blue food proteins in the field of functional food and drug development. By further exploring the mechanism of bioactivity of these proteins, more innovative solutions for human health may be possible.

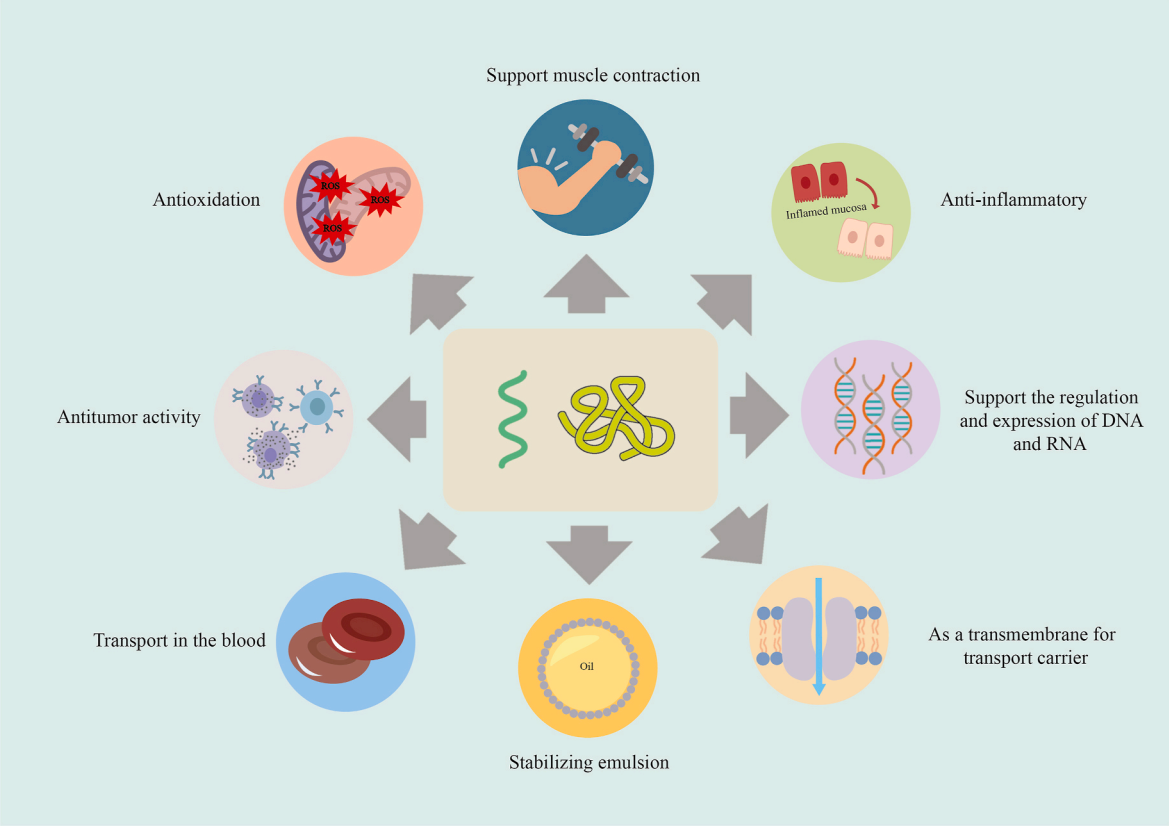

Fig. 3. Some properties of blue food proteins. (A) Nutritional properties: Support muscle contraction, etc. (B) Functional properties: Stabilizing emulsion, etc. (C) Bioactivities: Antioxidant, antibacterial, anti-inflammatory, etc. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

4. Applications of blue food proteins

4.1. Routine application of blue food proteins

4.1.1. Emulsions

Blue food proteins are amphiphilic and can spontaneously adsorb at the water-oil interface and are natural emulsifiers (Han et al., 2022; Rawiwan et al., 2022). The emulsification capacity of blue food proteins was related to pH value. Sun et al. (2022) found that the best emulsification capacity of golden pompano protein was achieved with an EAI and ESI of 42 m^2/g and 92 min, respectively, at pH 3.0. This was attributed to the reduction of the interfacial tension at this condition, which promotes a uniform distribution of proteins at the water/oil interface. Moreover, if the oil-water ratio was adjusted to 5:5 (v/v), the golden pompano protein was better for the long-term stabilization and preservation of the emulsion. Appropriate ultrasonication improves the emulsification capacity of the protein and makes it more suitable as an emulsifier, as demonstrated in the study by Yu et al. (2022), the results showed that the EAI and ESI of mussel myofibrillar proteins were significantly increased to 33 m^2/g and 78 min, respectively, under ultrasonication at 20 kHz, 450 W, and 16 min. The authors attributed the increased hydrophobicity and solubility, and the reduction of the particle size after the ultrasonication treatment were responsible for the increased emulsification capacity. In addition, mussel myofibrillar proteins treated by ultrasound had a positive effect on the storage stability of the emulsions. Blue food proteins can also be used as emulsifiers to protect and deliver substances. Zhang et al. (2021) used cod protein-chitosan nanocomposite particles as emulsifiers to stabilize a high internal phase Pickering emulsion, a system with a dense three-dimensional network structure, which could lead to a bioavailability of astaxanthin up to 49% and provide a feasible method for the delivery of hydrophobic bioactive compounds.

4.1.2. Protein films

With consumers' increasing demand for food safety and worry about environmental pollution, some materials of natural origin have great development space. In terms of food preservation, protein films have gained great attention due to the advantages of the wide source of protein, good film-forming properties and degradability (Calva-Estrada et al., 2019). Moreover, it is common to combine proteins with some other substances to make them better film-forming or to obtain biological activity. Bhuimbar et al. (2019) extracted acid-soluble collagen from Medusa fish skin and blended it with chitosan to develop a collagen-chitosan food packaging film, which has good mechanical strength and better water solubility. At the same time, a certain amount of pomegranate peel extract (with a high polyphenol content) was added to confer antimicrobial activity to the film. Similarly, Zhao et al. (2022) prepared a nanocomposite antioxidant film based on silver carp myofibrillar protein with the addition of oxidized polyphenol cross-linking agent and combined with layered double hydroxides (nanofillers), it was found that the tensile strength was up to 17.4 MPa, and the permeability of water vapor and oxygen, and the thermal stability were improved, and it had a good antioxidant ability. Ghaderi et al. (2019) prepared a ternary film using chitosan, polyvinyl alcohol and fish gelatin as materials, the addition of fish gelatin improved the toughness, elasticity and thermal stability of the film, and improved the barrier to UV and visible light, and this environmentally friendly and highly versatile ternary film has a great potential for development.

4.1.3. Microcapsules

Microcapsule is a technology that utilizes wall-formable materials to form a specific structure, which in turn can encapsulate the substance inside the capsule and play a role in protection, delivery, and slow release, and is widely used in the fields of medicine, food, cosmetics, and agriculture (Han et al., 2022). Proteins have good film-forming properties and are an important choice for microcapsule wall materials. Wang et al. (2021) used a pH-driven method to encapsulate curcumin in cod protein to make cod protein-curcumin nanoparticles. It was found that curcumin was doped during the rearrangement of cod protein with a doping rate of 99.50%, and the main force between the two was hydrophobic interaction. The nanoparticle structure greatly improves the light and heat stability of curcumin. Microcapsules made of blue food proteins are also used for probiotic protection. Zhang et al. (2022) prepared microcapsules of *Lactobacillus reuteri* using modified tilapia fish skin gelatin (transglutaminase-modified) with a cross-linking degree of 15.45%, which greatly improved the storage stability and survival in simulated gastrointestinal fluids of *Lactobacillus reuteri*.

4.1.4. Food colorant

With the increasing attention of consumers to healthy diets, the application of natural food colorants is becoming more and more promising. Due to its vivid blue color and good water solubility, phycocyanin can be used as a natural food colorant to be added to foods such as candies, beverages, ice creams, etc. The study by García et al. (2021) demonstrated that C-phycocyanin showed excellent performance and stability in its application as a beverage colorant, and its color and functional properties remained unchanged throughout the study. This result further demonstrates the remarkable potential of phycocyanin as a natural food colorant.

4.1.5. Dietary supplement

Calcium is the most abundant metallic element in the human body. It is not only the main component of bones and teeth, but also plays an important role in a variety of physiological processes such as nerve conduction, muscle contraction and blood clotting. Calcium deficiency can lead to a range of health problems, so improving calcium absorption is especially important for individuals suffering from calcium deficiency. It has been found that hydrolysates and bioactive peptides from blue food proteins have significant calcium chelating capacity and can effectively promote calcium absorption. For example, tilapia muscle protein, bone collagen, skin gelatin and Antarctic krill protein hydrolysates have shown potential to enhance calcium absorption (Lin et al., 2024). This provides a new research direction and application prospect for utilizing functional components from blue food sources to improve calcium absorption.

4.2. Application of blue food proteins in future food

4.2.1. 3D printing

3D printing is a cutting-edge technology that creates three-dimensional objects through computer software and produces products by laying down thin layers of material in a continuous process, which has been used in a number of industries and fields, such as mechanical engineering, aerospace engineering, biomedical engineering, and the pharmaceutical and food industries (Portanguen et al., 2019). 3D printing is more customizable (food shapes, nutritional ratios, etc.), flexible, and cost-effective than traditional food processing, and it can produce artistic shapes and designs of high complexity (Bhat et al., 2021; Wang et al., 2022). Therefore, 3D printing has received increasing attention. Fused deposition modeling is the most common and typical application of 3D printing in the food field, this requires that the food material used for 3D printing be homogeneous, fluid, and stable, so that the molded structure does not collapse prematurely and to ensure its stability during the layering process. Surimi has these properties and can be used as an ink for 3D printing (Dong et al., 2020). In addition, the addition of some substances can also improve the properties of surimi gel. Wang et al. (2018) investigated the effect of NaCl addition on surimi gel as a 3D printing material, and found that the addition of NaCl weakened the elastic component and viscosity of surimi, and increased the water holding capacity, which was more favorable for the outflow of the slurry; compared with the control group, the strength of the gel increased by 2 times, which will help to support its weight during 3D

printing. This suggests that 3D printing with surimi gel as ink is a promising method for food production. In addition, 3D printing is highly customizable, making it suitable for food production for special populations (elderly, children, athletes). Xie et al. (2022) investigated a 3D printing ink suitable for the nutritional needs and texture of the elderly - dietary fiber, flaxseed oil and cod protein gel composite system, dietary fiber and flaxseed oil to play the role of "embedding" and "filling" to make the system more suitable for 3D printing. In addition, the addition of the two substances significantly reduces the gelation and hardness of the cod protein gel, improving its swallowing ability. Blue food proteins are also used to stabilize Pickering emulsions as inks for 3D printing. Wang et al. (2022) investigated the effects of phycocyanin on the physicochemical, structural, extrudability, thixotropy and practical printing properties of gelatin-based high internal phase emulsions. It was found that electrostatic interactions and hydrogen bonding between the two substances promoted the dense structure of the high internal phase emulsions, enhanced the stability of the emulsions, and reduced the emulsification index of the emulsions. Shear-thinning properties and appropriate yield stresses proved the excellent extrudability of the emulsions. In addition, thixotropy results demonstrated excellent structural reconstruction ability and structural maintainability. It is suitable for 3D printing.

4.2.2. *Cultured meat*

As the population grows, the demand for meat continues to increase. Therefore, there is a need to seek more sustainable methods of meat production. One good way forward is cultured meat. Cultured meat is an artificial meat in which cells are allowed to grow and multiply in large quantities in a nutrient-rich culture medium without slaughtering livestock, poultry, animal blue foods, etc., and then the cells are transferred out and allowed to differentiate into muscle tissue (Park et al., 2021). Cultured meat is a disruptive future food production technology, involving the integration and comprehensive use of technologies from multiple disciplinary fields such as cell biology, materials science, tissue engineering, fermentation engineering, and food engineering (Ye et al., 2022). Blue food proteins are also used in cultured meat production. Lee et al. (2022) adjusted the ratio of fish gelatin/agar matrix and covered the optimized system on the surface of textured vegetable protein by a simple and rapid dipping method, which increased the system's ability to adhere to the cells, making a useable cultured meat scaffold, and ultimately resulted in cultured meat with a texture, flavor, and taste that was similar to that of slaughtered meat. In this system, the fish gelatin acts to increase cell adhesion. Currently, cultured meat technology is in the developmental stage and has some limitations, such as the need to use excessive and expensive serum to provide nutrients for cell proliferation. To address this shortcoming to some extent, Park et al. (2021) used C-phycocyanin instead of serum while designing a platform of polysaccharide films for delivery of C-phycocyanin to myoblast, which was composed of a porous structure formed by molecular reorganization of chitosan and cellulose and covered with an agarose film. The porous structure and the agarose film served to contain and protect C-phycocyanin, respectively. The results show that this study reduces the use of serum while ensuring large cell proliferation and maintaining cell health in the unfavorable environment of long-term culture. Some applications of blue food proteins are shown in Fig. 4.

5. Conclusion and future perspectives

Blue food proteins have a balanced amino acid composition, high digestibility and absorption rates, excellent nutritional properties, and are not subject to religious constraints, so their development is an important measure to deal with future protein and food security. With

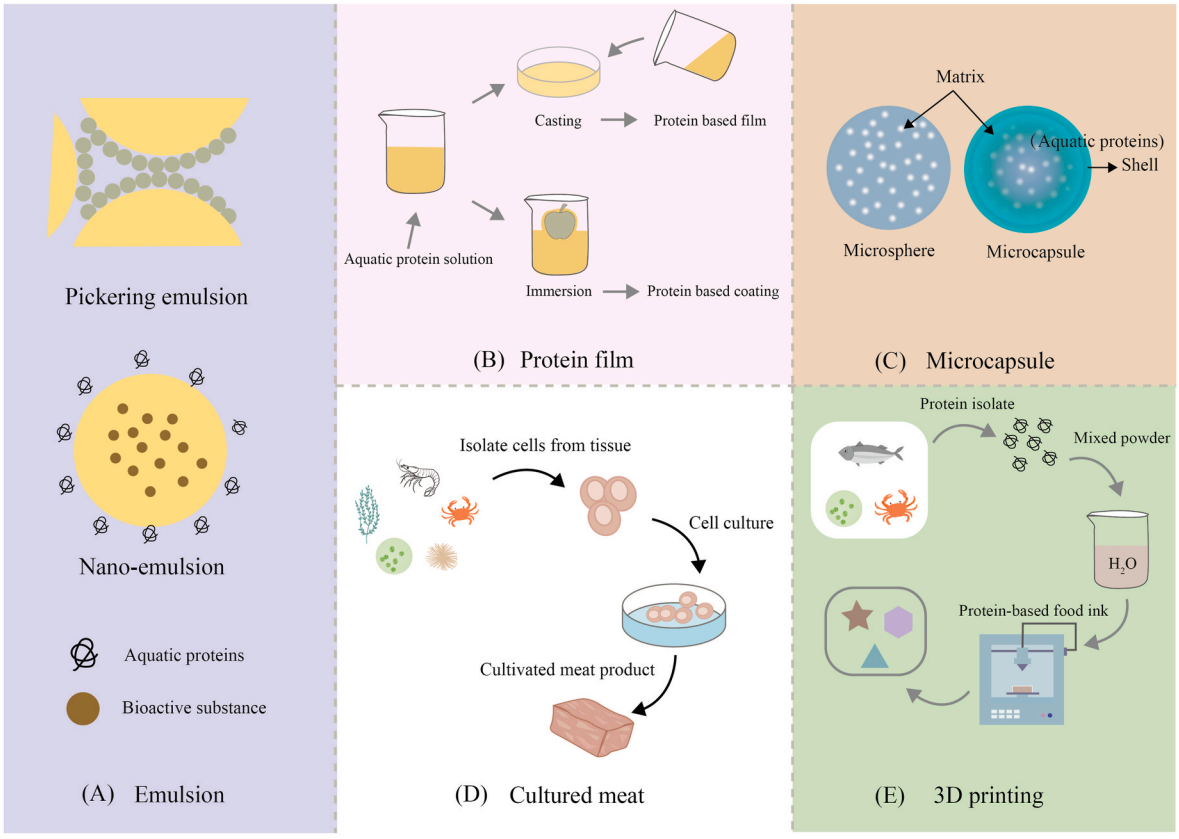

Fig. 4. Some applications of blue food proteins. (A) Stabilizing emulsion. (B) Protein film. (C) As the material for microcapsules. (D) As a scaffolding and potential medium for cultured meat. (E) Inks for 3D printing. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

the increasing global demand for sustainable food, blue food proteins are becoming an important research area in the food field.

Novel blue food protein extraction technologies, such as MAE and UAE, have demonstrated significant advantages in terms of improving extraction efficiency, reducing energy consumption and minimizing environmental impact. However, at this stage, most of these technologies are in the experimental stage, and further optimization of equipment and process conditions is still needed to meet the demands of industrial applications and ensure their economic feasibility and sustainability.

Blue food proteins are not only a high-quality source of protein, but also have excellent functional properties and great prospects for development in food production. In addition, blue food proteins have biological activities, such as antioxidant, heavy metal adsorption, anti-inflammatory, etc., which can be used to develop functional foods. In the future, blue food proteins will play an important role in cutting-edge fields, such as 3D-printed food and cultured meat. Meanwhile, improving the processing performance and functional properties of blue food proteins through appropriate modification techniques to adapt them to a wider range of food applications is also an important direction for future research.

In summary, blue food proteins show significant advantages in terms of nutritional value, functional properties and sustainability. With the continuous innovation and optimization of extraction technologies and processing methods, the application of blue food proteins in the future food industry is very promising, and they will certainly play a more important role in the global protein supply chain.

CRediT authorship contribution statement

Shuo Fan: Conceptualization, Writing – original draft. **Yaxin Yin:** Visualization, Designed the figure. **Qirui Liu:** Visualization. **Xinru Yang:** Visualization. **Daodong Pan:** Writing – review & editing. **Zhen Wu:** Writing – review & editing. **Ming Du:** Conceptualization, Writing – review & editing, Funding acquisition. **Maolin Tu:** Supervision, Writing – review & editing, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

No data was used for the research described in the article.

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