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SEAWEED PEPTIDE AS NOVEL PROTEIN ALTERNATIVE: A SUSTAINABLE APPROACH FROM SEA TO SUSTENANCE

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Abstract

Seaweeds, a broad and diverse range of marine macroalgae, have emerged as viable and sustainable protein sources that can meet the increasing worldwide demand for nutritious food. They are highly esteemed for their high protein content, particularly in red and green macroalgae species, whose protein outputs frequently exceed those of terrestrial plants and are comparable to animal proteins. On the contrary, the sustainable farming of seaweeds requires minimal resources: no arable land, minimal or no freshwater, and no fertilisers, thereby enhancing climate resilience, promoting nutrient cycling, and conserving the health of marine ecosystems. Notwithstanding these benefits, the practical implementation of seaweed proteins encounters obstacles pertaining to extraction, digestibility, and processing. This review examines seaweed proteins as innovative dietary alternatives, emphasising their comprehensive amino acid profiles, bioactive constituents, extraction techniques, and uses in functional meals. The discourse addresses the nutritional potential and technological challenges of utilising seaweed proteins, as well as their prospects for promoting a more sustainable, health-oriented food system.

Keywords: Seaweed protein; Amino acids; Functional food; Protein extraction; Bioactive compounds

1. Introduction

The growing populations and shifting dietary preferences create a persistent demand for protein, which presents numerous challenges concerning the sustainability of the environment and resource depletion [1]. As a result, various substitutes for protein are under investigation, with the potential to be both nourishing and sustainable. In this context, seaweed, a varied habitat of ocean macroalgae, presents an intriguing option by offering high protein content along with various essential amino acids [2].
Seaweed proteins present a transformative opportunity to sustainably address the increasing global demand for protein, providing distinctive nutritional and functional characteristics that set them apart from traditional protein sources [3]. For example, red and green macroalgae comprise 47% dry cell weight (dw) protein, which is much higher than that of terrestrial plant sources and comparable to various animal products [4]. Additionally, animal protein sources such as egg and casein exhibit levels of protein of 51% and 67–78% dry weight, respectively, while two red algae, *Macrocystis pyrifera* and *Hondracanthus chamissoi*, have been reported to have protein contents of 62% and 45% dw, respectively [5].
On the other hand, the sustainable cultivation of seaweeds necessitates minimal resource inputs, including no arable land, little to no freshwater, and no fertilisers, thereby conferring an environmental benefit that underpins efforts in climate mitigation, nutrient cycling, and the preservation of marine ecosystem health. Furthermore, seaweed cultivation promotes the development of coastal economies and can be combined with various aquaculture practices to improve overall productivity and biodiversity [6].
Despite all these advantages, the commercial utilisation of seaweed protein remains challenging. Therefore, this review aims to provide a brief discussion on seaweed protein as a novel food alternative, including its component amino acids and digestibility. Furthermore, the complexity of protein extraction presents technical challenges that will also be addressed in this review, as well as in the context of functional food applications.

2. Seaweed protein

Seaweeds are a rich source of protein, with some species containing up to 47% dry weight (dw) protein. However, protein content varies among different types of seaweed. For instance, brown algae typically have lower protein levels, ranging from 3-15% dw, whereas red algae exhibit higher values, often between 8-47%; dcw. On the other hand, green algae generally possess moderate to high protein content, typically reported to be between 9-26% dry weight (dw). Notably, the protein concentrations in particular red and green seaweed species surpass those of protein-rich plants, such as soybeans, which contain about 38% dry weight protein [7].

2.1. Amino acid composition

Seaweed proteins are notable for their diverse amino acid profiles, which vary among species but typically encompass a diverse array of amino acids, both essential and non-essential. Numerous compounds demonstrate bioactive properties, such as anti-oxidant, antibacterial, and antiviral in nature activities, which are linked to the health advantages of seaweed consumption [8]. Seaweeds provide all essential amino acids necessary for human nutrition, including significant amounts of glycine alanine, arginine, proline, glutamic acid, and aspartic acid where leucine is frequently the most abundant essential amino acid. across various seaweed species, followed by valine, threonine, and phenylalanine [9].

Table 1: Assessment of protein and amino acid composition of different seaweeds [9]

Seaweed	Protein (% dry weight)	Amino acids				
		His	Leu	Met	Cys	Tyr
Ulva pinnatifida	12.5	21.6	89	30.9	65.8	61
Porphyra umbillicalis	39	15.7	76.8	8.7	67.2	46.2
Ulva fasciata	7.1	13.1	40	6.1	0	36.3
Porphyra palmata	15.2	18.5	65	28	6.7	47.4

Note: His: Histidine, Leu: Leucine, Met: Methionine, Cys: Cysteine, Tyr: Tyrosine.

Brown seaweeds, including *Alaria esculenta* (Irish wakame) and *Himanthalia elongata* (marine spaghetti), along with red seaweed species such as *Porphyra umbilicalis* (Nori), regularly exhibit leucine as the predominant essential amino acid (Fig.1). Valine and leucine are particularly abundant in green seaweed species, including *Ulva lactuca* (Table 1). Aspartic acid and glutamic acid make up a significant component of the total amino acid composition in numerous types of seaweed, contributing to their distinctive flavours and the umami taste profile that characterises many edible seaweeds [7].

2.2. Amino acid ratio

Various studies have assessed the protein quality of seaweeds using metrics such as the Essential to non-essential amino acid ratios (EAA/NEAA and EAA/total AA), as well as indexes such as the amino acid essential index (EAAI) and amino acid score. Seaweeds typically contain 37.7-48.4% EAA, including EAA/NEAA proportions ranging from 0.65 to 1.61. Red seaweed has a higher total protein content, but it has a reduced percentage of EAAs per gram of protein, or a lowered EAA/NEAA ratio. ratio compared to other groups [10].

Research indicates that the proportion of EAA compared to total amino acids (AA) in brown seaweeds like *Ascophyllum nodosum*, *Fucus vesiculosus*, and *Bifurcaria bifurcata* falls within the range of approximately 39% to 41% [11]. Conversely, certain Indian edible seaweeds, including Acanthophora spicifera, *Gracilaria edulis*, *Padina gymnospora*, and *Ulva lactuca*, are noted. *Flexuosa* has essential amino acid (EAA) percentages between 41% and 50%, and an EAA-to-non-essential amino acid (NEAA) ratio varying from 0.72 to 1.02. *Sargassum polycystum*, another species of brown seaweed, exhibits an EAA-to-total AA proportion of roughly 0.5 and an EAA-to-NEAA proportion of nearly 1.0 [11]. Among red seaweeds, *Gracilaria corticata* and *G. edulis* demonstrate favourable ratios of EAA to NEAA at 0.62 and 1.19, respectively, with EAA to total AA ratios of 0.29 and 0.54 [12]. These findings highlight the nutritional value of seaweed proteins and their potential as a dietary protein source.

3. *Other functional properties of seaweed proteins*

Along with different amino acids, seaweed proteins contain a variety of bioactive compounds, such as lectins, phycobiliproteins, and glycoproteins, with potential health benefits.

3.1. Lectins

Lectins, also called agglutinins, are proteins found in a wide variety of species that have a tendency to connect with carbohydrate moieties [13]. Prior research has characterized mannose-specific lectins from red algae. Barre et al. [14] categorize mannose-specific lectins derived from seaweeds into five distinct classes according to their structural frameworks. These lectins demonstrate anticancer and anti-HIV effects.

3.2. Phycobiliproteins

Phycobiliprotein is a characteristic chromoprotein found in red algae. Phycocyanin, a pigment that imparts a blue-green hue to specific seaweeds, is a significant bioactive chemical present in seaweed proteins. Phycocyanin has been studied for its anti-inflammatory and antioxidant qualities, which may have an impact on immune system and cardiovascular health, among other aspects of human health [15]. In addition to its antioxidant and anti-inflammatory in nature characteristics, spirulina has been studied for the possibility to improve lipid profiles, reduce blood pressure, and augment immune function [16].Phycobiliprotein particularly R-phycoerythrin is a major pigment found in red seaweed which has high commercial value in biomedical as well as food industry [15].

3.3. Glycoprotein

Glycoproteins in the structure of cells wall function as the primary protein type in the majority of seaweeds [17]. The carbohydrate fraction accounts for roughly 90% dry weight, primarily consisting of arabinose and galactose remnants. The protein fraction predominantly consists of hydroxyproline residues, which constitute around 10% dw [18]. Additionally, the glycoprotein extracted from *Codium decorticatum* comprises 36.2% dw carbohydrate.

The carbohydrate component comprises monosaccharides: rhamnose, galactose, glucose, and mannose, present in a molar ratio of 38:30:26:6. [18] This structure is composed of protein and carbohydrate, specifically containing (1→4)-linked β-galactose and connected glucose remnants. Glycoproteins demonstrate efficacy in the cells of algae and in human beings upon consumption as a dietary component. Algal glycoproteins exhibit various biological properties, such as promoting cell proliferation, providing hepatoprotection, demonstrating anticancer effects, exhibiting anti-inflammatory activity, offering protection against Alzheimer's disease, displaying antiviral properties, and possessing antioxidant activities. Glycoproteins derived from the marine green algae Codium decorticatum demonstrate anticancer effects, specifically against human breast cancer cells. The MCF-7, Siha, and A549 cell lines showed suppression at concentrations of 60, 75, and 55 μg/mL of glycoproteins, accordingly, following 24 hours of incubation [19]. The glycoprotein derived by the brown algae *Saccharina japonica* demonstrates antioxidant properties, evidenced by DPPH radical-scavenging capacity and superoxide dismutase enzyme activity recorded at 85% and 94%, respectively, along with protective effects on DNA.

Fig. 1: Some edible algae species. (A) *Ulva lectuca*; (B) *Codium fragile*; (C) *Caulerpa sertularioides*; (D) *Halimeda* spp.; (E) *P. palmata*; (F) *Hypnea pannosa* (G) *Padina* spp. (H) *Sargassum* spp. Photocourtesy by Piyumika Madhushani [7].

4. Different extraction processes of seaweed protein

Seaweed has limited digestibility of proteins in its natural state due to its intricate cell wall, which makes digestion difficult without the use of digestive enzymes. Thus, protein methods for extraction are required to improve its digestibility. To extract protein from dried seaweed powders, various methods, including physical, chemical, enzymatic, and novel approaches, can be employed. Protein can then be extracted via centrifugation or filtration. Dissolved protein can be retrieved and purified via ultrafiltration, liquid chromatography-based dialysis, and centrifugation. High-purity proteins are necessary for developing functional foods, but not for conventional food and feed production. Preconcentration and drying procedures (freeze-drying and oven-drying at 40℃) can preserve isolated protein [20]. Figure 2 illustrates the extraction methods and processing strategies for acquiring seaweed proteins, which encompass multiple stages designed to effectively isolate and purify proteins from seaweed biomass.

Table 2: Different protein extraction methods and yields from seaweeds [7]

Species	Extraction process	Protein yield (% dry weight)
Alaria esculenta	High-pressure extraction	15
Chondrus crispus	Osmotic shock	35.5
Fucus vesiculosus	Autoclave extraction	24.3
Ulva lactuca	Enzyme extraction with papain	69.2
Palmaria palmata	Enzymatic treatment with Viscozyme	35.5-41.6
Pyropia palmata	Autoclave	21.5

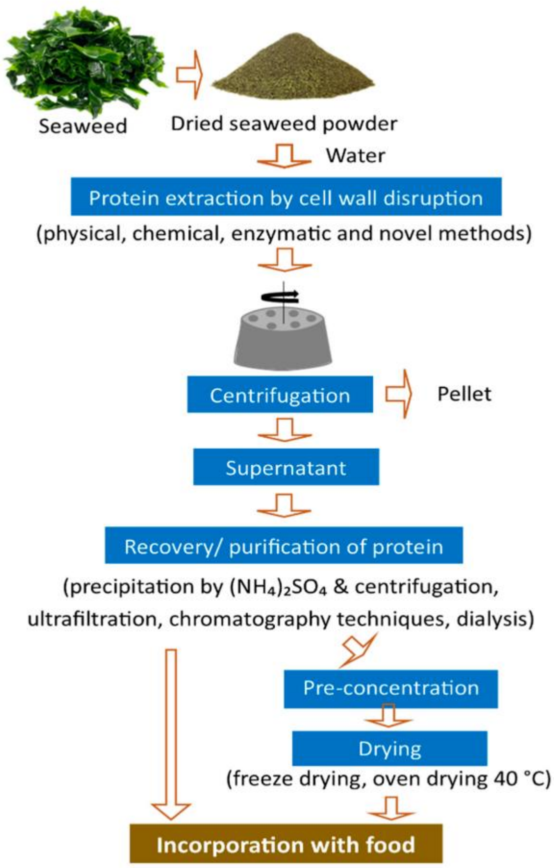

Fig. 2: Sequential pathway for seaweed protein extraction methods [7].

Extraction Methods frequently differ based on the specific traits of the species of seaweed and the targeted properties of the extracted proteins . Alkaline extraction employs solutions that are alkaline, such as sodium hydroxide, to disrupt cell walls and release proteins from the seaweed framework. Enzyme-assisted extraction employs enzymes, including proteases, to degrade protein structures and improve their extraction efficiency (refer to Table 2).

Various extraction methods, including maceration, filtration, and precipitation stages, are used to isolate proteins from seaweeds, as mentioned in Table 2.

5. Application in functional food

Seaweed-derived proteins are widely used to enhance the nutritional content, texture, and sensory qualities of a diverse range of food products, particularly in plant-based and vegan formulations that aim to replace traditional animal proteins. These protein isolates and concentrates derived from seaweed are incorporated into meat alternatives, dairy substitutes, snacks, baked goods, and beverages, where they not only enhance protein levels but also provide essential amino acids and beneficial bioactive compounds. In addition to their nutritional roles, seaweed proteins serve as functional ingredients that act as emulsifiers, stabilisers, and texturisers, resulting in enhanced texture and mouthfeel in food products [21].

Irish moss (*Chondrus crispus*), a red seaweed native to the Atlantic, offers a moderate protein content and serves as a primary source of carrageenan, a polysaccharide commonly used for thickening foods. Besides proteins, Irish moss contains a high concentration of vitamins, minerals, and antioxidants, and is traditionally used to support respiratory and digestive health. Sea lettuce (*Ulva* spp.), a globally distributed green macroalga, offers moderate protein content and is abundant in vitamins A, C, and K, along with minerals including iron and iodine. Ulva includes chlorophyll and polyphenols, which are known for their antioxidant and anti-inflammatory properties that may enhance overall well-being [22].

Seaweed proteins have gained a prominent place in dietary supplements, marketed for athletes and health-conscious consumers seeking to increase protein intake. These supplements often combine with other nutrients to provide comprehensive support for immune function, digestive health, and the condition of the skin and hair. For example, various species, including Nori (formerly *Porphyra* spp.), *Gracilaria*, *Sargassum wightii*, and *Eucheuma*, have been incorporated into foods and beverages such as wine, soups, noodles, jams, cheeses, and sausages to enhance their nutritional profiles [23]. These promising results underscore the potential of seaweed proteins as preventive and therapeutic agents for managing oxidative stress, inflammation, and microbial infections .

Along with protein, seaweeds have garnered significant attention over recent decades due to their abundance of bioactive compounds. Hydrocolloids, including agar, alginates, and carrageenan, along with alkaloids, carotenoids, polyphenols, terpenes, tocopherols, laminarin, and fucoidan, are extensively used as functional ingredients in bakery, dairy, fish, meat, and vegetable-based foods [24].

Incorporating *Undaria pinnatifida* (wakame) into pasta enhances its bio-functional properties by improving starch-protein interactions. Certain seaweeds, such as *Caulerpa racemosa* and *Ulva lactuca*, possess excellent amino acid profiles rich in lysine and methionine, making them suitable for use in nutritious food formulations, particularly when combined with cereals and legumes, to provide balanced diets. Furthermore, *Saccharina japonica* (formerly *Laminaria japonica*) has historically functioned as a flavor enhancer in Japanese gastronomy. Free amino acids, such as glutamic acid, aspartic acid, alanine, and glycine, provide to the distinctive umami and sweet flavors of seaweed [25].

6. Bioavailability of seaweed protein

Most seaweed proteins are easily digestible and bioavailable, which makes them especially helpful for people who have stomach problems or who are looking for other protein sources. These properties enhance their suitability in specialised diets and for individuals aiming to optimise nutrient absorption from plant-based proteins [26].

The bioavailability of seaweed proteins is a crucial determinant of their nutritional value, referring to how effectively amino acids or small peptides from consumed seaweed proteins are absorbed into the body after crossing the intestinal lining. In vitro digestibility studies, which are rapid and economical, are commonly used to estimate both the digestibility and availability of food proteins, including those from seaweeds. These assessments typically employ combinations of proteolytic enzymes such as pepsin, trypsin, pancreatin, or chymotrypsin, which mimic the action of mammalian gastric, pancreatic, and intestinal enzymes to simulate digestion outside the body. This enzymatic approach helps researchers understand how efficiently the human digestive system can access the nutritional components of seaweed proteins [27].

Among the three main groups of seaweed, red seaweed shows the highest protein digestibility. Its values are about the same as those of a number of plant-based foods, like grains, legumes, fruits, and vegetables. They are only slightly lower than those of casein and whey, which come from animals. In in vitro studies, the digestibility of brown seaweed, specifically *Undaria pinnatifida*, varied significantly depending on the enzyme used. It exhibited a digestibility of 17% with pepsin at an acidic pH and 66.6% with pancreatin at a neutral pH. When both pepsin and pancreatin were combined, *Porphyra columbina* showed a digestibility of 74.3% [28].

On the other hand, the presence of polysaccharides, especially soluble fibres like xylan and carrageenan in seaweed, can hinder protein breakdown. These substances may interact with proteins or enzymes, reducing digestion efficiency. Additionally, in *Ulva armoricana*, it has been observed that the glycoproteins and the degree of glycosylation slow down the enzymatic hydrolysis rates of trypsin and chymotrypsin [29]. High levels of soluble fibres also contribute to decreased digestibility, particularly in species such as *Porphyra palmata* and *Gracilaria longissima* [30].

7. Conclusions

High-value functional foods, especially those made with natural ingredients rather than artificial ones, are in greater demand as consumer interest in nutrition and health continues to rise. Consequently, the use of seaweed-derived proteins in functional food development has increased over the past decade. Moreover, their amino acid profile and digestibility are comparable to, or even exceed, those of animal proteins. Most seaweed species contain more than 50% essential amino acids within their total amino acid content. Many bioactive substances, including amino acids, free amino acids like taurine, peptides, phycobiliproteins (including phycoerythrin and phycocyanin), and lectins, are found in the protein fraction of seaweeds. Antihypertensive, antioxidant, antidiabetic, antiatherosclerotic, anti-inflammatory, antitumoral, antibacterial, antiviral, and neuroprotective actions are only a few of the many health advantages that these substances provide.

Additionally, seaweeds serve as natural food additives, offering colourants, flavour enhancers, antioxidants, preservatives, and other health-promoting compounds. Despite these advantages, seaweed proteins remain underutilised in the food industry, and there is limited research on their acceptability, safety, allergenic potential, and microbial impacts.

It is anticipated that further scientific and technological advancements will make algae-based proteins more widely accepted as sustainable alternatives, thereby supporting a more environmentally conscious food system. Nevertheless, additional research is required to uncover more health-promoting bioactive compounds while minimising potential biochemical or microbiological risks associated with seaweed use, refining extraction techniques, ensuring consumer safety, and tackling issues related to sustainable aquaculture and efficient processing.

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