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Extraction of fucoidan from brown algae and its application in the food industry

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ABSTRACT

Fucoidan is a sulfated polysaccharide from brown seaweed consisting of several monosaccharides found in the cell wall of brown seaweed and composed of resistant cellulose and hemicellulose. This bioactive compound has several bioactive properties such as antioxidant, antimicrobial, antiviral, hypolipidemic, anticancer and tumorigenic, anti-inflammatory and immunomodulatory. Due to their natural nature and virtually non-toxic nature, they are considered as a promising antimicrobial component for various applications in medicine and food industry. The properties of fucoidan depend on several factors, including molecular weight and extraction method. The molecular weight of fucoidan, related to its biological activities and bioavailability, can be influenced by extraction technologies. A wide range of extraction methods are currently used to obtain these polysaccharides, such as supercritical fluid extraction (SFE), pressurized liquid extraction (PLE), subcritical water extraction (SCWE), ultrasound-assisted extraction (UAE), enzyme-assisted extraction (EAE), and microwave-assisted extraction (MAE). Given that an increasing number of studies have shown the extraction process of fucoidan in the past few years, and the use of fucoidan synthesis is an effective strategy in the development of bioactive films in food coatings, which will reduce the reliance on plastic materials and increase the shelf life of food products. This review presents the conventional extraction and purification processes, physicochemical and biological activities, and structural characterization, and recent advances in the application of fucoidan in the food industry.

1-Introduction

Due to the increasing consumer awareness of functional foods, seaweeds are increasingly considered as potential sources of bioactive compounds. Seaweeds are divided into three groups based on their pigments: green algae (Chlorophyceae), red algae (Rhodophyceae), and brown algae (Phaeophyceae). With approximately 2000 species, brown seaweeds are the second most abundant group of seaweeds [1]. Each group has unique characteristics and different benefits. A diverse collection of seaweed species, including approximately 900 green species, 4000 red species, and 1500 brown species, exist in nature. Currently, approximately 221 species are harvested worldwide, including 32 Chlorophyceae species, 64 Phaeophyceae species, and 125 Rhodophyceae species, of which the brown seaweed genus Sargassum constitutes the largest natural resource in the Vietnamese Sea [2]. Brown seaweeds, which are widely found in the Atlantic Ocean, are mainly composed of protein, lipids, polysaccharides, pigments, vitamins, dietary fibers, and minerals. The key component in brown seaweeds is polysaccharides, which mainly include three types of biopolymers: fucoidan, alginate, and laminarin [3]. A variety of bioactive compounds are obtained from these components (Figure 1), including fucoxanthin, fucoidan, laminarin, peptides, mannitol, and polyphenolic compounds. These bioactive compounds exhibit a variety of biological activities, such as antimicrobial, antioxidant, antifungal, antiviral, anticancer, anticoagulant, antidiabetic, anti-HIV, anti-inflammatory, and so on [4]. In general, the protein content in seaweeds varies between 3 and 45%, and the carbohydrate content ranges between 4 and 67%. Additionally, seaweed is known to have a low fat content, typically below 8%, while brown seaweed is generally known to be high in carbohydrates.

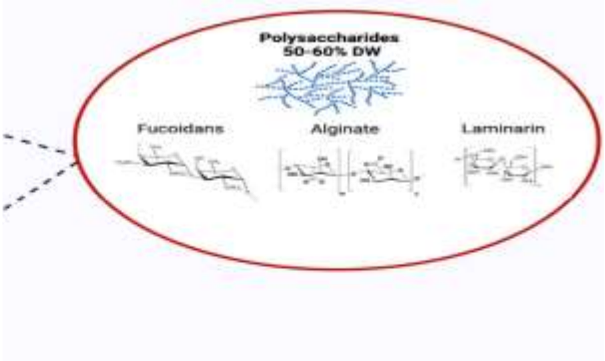

Fig1. Scheme showing the composition of brown algae [5].

Fucoidan is also considered a valuable ingredient in the food industry due to its emulsifying properties, and fucoidans have the highest uronic acid content and the highest free radical scavenging activity [6]. In particular, there is a growing demand for the isolation of bioactive peptides from seaweed. About 25–30% of the dry weight of brown seaweed is composed of fucoidan. Fucoidan has different molecular weights, depending on the extraction method.

Typically, 100~1000 kDa is known. Fucoidan is a sulfated polysaccharide enriched in L-fucose sulfate with small amounts of other monosaccharides such as glucose, galactose, mannose, etc. This compound can be found in a variety of brown seaweeds including Laminaria sp., Fucus sp., Sargassum sp., etc. [7]. The bioactivity of fucoidan can be affected by factors such as the specific source of brown seaweed, the levels of sulfate and fucose, the types of monosaccharides present, the extraction method, or biotic and abiotic factors [6]. Different extraction methods affect the nature of fucoidans and at the same time change their chemical structure. Extraction conditions include extraction time, extraction temperature, solvent, cycle time and extraction power. Typically, seaweed polysaccharides are extracted through aqueous extraction at different pH values, which usually use strong acids and bases or sodium chloride solution and hydrothermal treatment for initial extraction. Fucoidan is known to be soluble in hot water as well as acidic and saline solutions, usually higher temperature is required for extraction of fucoidan with water solvent [8]. For this reason, water extraction methods are not very efficient due to the need for a large volume of water resources and chemicals, as well as long extraction time (sometimes at high temperatures) and also due to the production of hazardous organic waste, and they can have a harmful effect on the biological activities of fucoidan [9]. Promising alternative methods including ultrasound-assisted extraction (UAE)[1], enzyme-assisted extraction (EAE)[2], pressurized liquid extraction (PLE)[3], microwave-assisted extraction (MEA)[4], supercritical fluid extraction (SFE)[5] and subcritical water extraction (SWE)[6] can be better technologies to achieve higher extraction efficiency [10]. A study conducted by Hans et al. in 2023 evaluated the impact of traditional and greener extraction techniques on fucoidan yield, monosaccharide composition, structural properties, and biological and laboratory activities of P. tetrastromatica and T. conoides. The results of this study showed that among the aqueous, chemical, SCWE, EAE and UAE methods, the SCWE method provided the highest fucoidan yield, i.e. 13%, in less extraction time. This study showed that by using the subcritical water method, the yield of fucoidan increased by 30% compared to the normal acid method. Also, the presence of high sulfate content (32.9%) and polyphenolic compounds increased the value of fucoidan and as a result its antioxidant activity, which may be industrially related to food and pharmaceutical industries [11].

2- Physical and chemical properties of fucoidan

Biological activities of fucoidan are influenced by characteristics such as degree of sulfate, monosaccharide composition, geographical location, extraction process, degree of exposure (mechanical stress), salinity (osmotic stress), harvesting time, and light, which affect the structure of fucoidan in algal species [12]. Various factors can affect the physical and chemical properties and yield and quality of extracted fucoidan, one of the most important factors is the extraction temperature, which can cause structural destruction of fucoidan and reduce its biological activity. Another important factor is the pH of the extraction environment, which strongly acidic or alkaline environment may change the chemical composition of fucoidan and affect its biological activity. Another factor is the extraction time so that Increasing the extraction time may increase the yield, but under inappropriate conditions it can lead to degradation of polysaccharides [13]. Saravana et al. (2016) investigated the emulsifying activities of fucoidan extracted from S. japonica. The results showed that fucoidan showed good emulsifying activity for sunflower, soybean and canola oils with emulsifying activities ranging from 40 to 60% [14]. In a study conducted by Hong Lee et al., the molecular characteristics and anti-inflammatory activities of fucoidan extracted from E. cava and fractionated by ion exchange chromatography were investigated. The extracted fucoidan mainly consisted of carbohydrates (51.8%), uronic acid (11.3%), and sulfates (20.1%), with small amounts of protein (8.7%). Ion exchange chromatography led to the identification of three fucoidans with different chemical compositions and molecular weights. These E. cava fucoidans showed a significant ability to reduce NO production from raw macrophages 7/264, suggesting that they may be potent anti-inflammatory agents. The present study highlights the potential applications of these fucoidans as pharmaceutical, medicinal, and functional food ingredients [15].

3- Extraction and Production of Fucoidans

A growing number of studies have investigated the extraction process of fucoidans in the past few years. The industrial economic value and rapid growth of marine algae have led to the

1 -Ultrasound-assisted extraction
2 -Enzyme Assisted Extraction
3 -Pressurized liquid extraction
4 -Microwave-Assisted Extraction
5 -Supercritical Fluid Extraction
6 -Subcritical Water Extraction

consideration of advanced technologies such as microwave and ultrasound technologies in augmenting existing processing methods [16]. These technologies, with different “action modes,” target the degradation of the cell walls of brown seaweeds, where most of the bioactive molecules, including fucoidans, are located. In fact, these methods can allow the use of water as an extraction agent with short operation times, and also different extraction methods can affect the chemical structures of fucoidans [17]. In addition, extraction depends on various factors such as solvent, extraction time, solid solvent ratio and extraction strength and cycle time. Higher extraction temperature increases the solubility of solutes and improves water transport properties, as well as increases diffusion and reduces viscosity, density and surface tension. This variable has a certain effect on selectivity, since the polarity of water can be adjusted by appropriate selection of pressure and temperature. Higher temperatures usually lead to rapid extraction and dissolution of apolar molecules, and the formation of new compounds with improved activity will also be observed. Temperature is also decisive in the release of compounds that form part of the cell walls [18]. The results of various studies have shown that one of the important factors in the production of fucoidans is the extraction time [19]. In fact, fucoidan extraction from brown seaweed species usually involves multi-step, hot acid or $CaCl_2$ treatments, each step of which may take several hours, but the use of alternative methods such as subcritical water extraction (SWE) can improve fucoidan yield due to the lack of chemical solvents and less waste generation [20]. Extraction of bioactive compounds involves several steps (sample preparation, pretreatment, extraction, polymer recovery and purification) and parameter optimization, and extraction methods can be classified into classical solvent methods and modern methods. Modern extraction methods such as supercritical fluid extraction (SFE), ultrasound-assisted extraction (UAE), enzyme-assisted extraction (EAE) and microwave-assisted extraction (MAE) are characterized by short extraction times, high production yields, and the use of small extraction volumes and non-corrosive solvents for the extraction cross-solution [21]. A study was conducted by Mohd Fauziee et al. in 2021, in which fucoidan, laminarin and alginate were successfully extracted from Malaysian brown seaweeds, namely S. polycystum, P. boryana and T. ornata. All these polysaccharides showed their distinctive properties. All these polysaccharides were considered relatively stable with water activity between 0.63 and 0.71 and appeared brownish in color. FTIR[7] analysis showed that these polysaccharides exhibited different functional groups, and it was also shown that polysaccharides from different brown seaweeds have different chemical structures. All the polysaccharides also showed different antioxidant activities, with the results of this study showing that fucoidans had strong DPPH free radical scavenging activities, while laminarins had strong OH radical scavenging activities [22]. In a study conducted by Laeliocattleya et al. in 2025, fucoidan extract from S. echinocarpum was specifically extracted to investigate its properties and antioxidant activity. The results showed that fucoidan extract contained fucose, sulfate and small amounts of galactose, mannose, xylose as well as amino groups and also had potential antioxidant activity that was affected by the extraction temperature and time, and the topology and morphology characteristics of the extract were also affected by the extraction treatment. In fact, appropriate extraction temperature and time resulted in increased antioxidant activity. Therefore, this study showed that investigating the properties and potential antioxidant activity of fucoidan extract from S. echinocarpum could provide an alternative to create a natural antioxidant, especially using brown seaweed that has not been optimally utilized [23].

3.1. Ultrasonic extraction (UAE)

A simple and effective method for depolymerization of fucoidan is the ultrasound method, which leads to a decrease in molecular weight without significant structural changes in

7- Fourier-transform infrared spectroscopy the macromolecules. Ultrasonic waves increase the efficiency of the mass transfer and extraction process and offer advantages such as low cost, ease of use, reduction of extraction time, energy, chemicals and solvents, as well as increased extraction yield compared to extraction with conventional solvents [24]. Ultrasonic extraction method is useful for extracting fucoidan from algae. This method is simple and can be used on an industrial scale. However, the use of ultrasonic method in combination with chemical (e.g., acidic, enzymatic) and physical (e.g., microwave irradiation) methods allows to increase the yield of the desired product [25]. Ultrasound equipment can be an ultrasonic bath (indirect sound) or an ultrasonic probe (direct sound). The difference between the two is in the operating conditions and the way in which the ultrasound waves affect the sample. The ultrasonic bath operates at a frequency of 40 to 50 kHz and a power of 50 to 500 W, but the ultrasonic probe operates only at a frequency of 20 kHz. The samples are immersed in the ultrasonic bath, while the ultrasonic probe is placed in the sample [26]. Ultrasound (US) waves, at frequencies in the range of 20 to 100 MHz, propagate through an elastic medium and induce successive compression and expansion cycles. This causes the phenomenon of cavitation, which leads to the generation, growth and collapse of bubbles filled with gas and vapor. The implosion of cavitation bubbles will cause microturbulence, high-velocity interparticle collisions, and turbulence in the fine porous particles, which will accelerate internal diffusion [27]. The high shear forces caused by cavitation near solids can cause surface exfoliation, erosion, and microfractures in more porous materials, which will facilitate solvent access to the target compounds. Although increasing temperature increases the solubility of solutes, careful control is required to avoid degradation of soluble compounds, adverse reactions, and cavitation control, as sonochemical effects are desirable at low temperatures. In order to maintain the temperature during extraction, thermostated baths or ice baths are used [28].

Ultrasound can also improve mass transfer and lead to higher product yields by reducing processing time and solvent consumption. In addition to these physical effects, chemical effects related to the presence of solvent vapor, high pressures and temperatures inside the cavitation bubble favor the extraction process [18]. Low-frequency ultrasonic exposure can be used for the polymerization of polymeric materials, including natural materials, and is used to separate polymers of various biopolymers, including polysaccharides, DNA, etc. without changing their chemical structure. Ultrasonic waves with a frequency of 16 kHz are used to reduce the molecular weight of polymers. Ultrasonic processing is based on the phenomenon of cavitation. As a result of cavitation, shock waves generate intense local heating (about 5000 °C) and high pressure (about 1000 atmospheres). Factors that affect the rate of polymer degradation during ultrasonic polymerization include ultrasonic intensity, extraction time and solution concentration, where increasing ultrasonic intensity produces more cavitation bubbles, which will aid the degradation process. [29] Ultrasonic time and power This can be explained by the fact that increasing the extraction time will facilitate the ability of the brown seaweed powder to contact the solvent. At the same time, higher ultrasonic power, which helps to break the brown seaweed cells, leads to a higher amount of fucoidan released into the solvent. However, excessively long extraction time (more than 50 min) combined with very high ultrasonic power (more than 360 W) will cause fucoidan degradation [30]. Studies on fucoidan extraction from Sargassum siliquosum, Sargassum mcclurei, Sargassum wightii and Sargassum muticum have shown the potential of ultrasound-assisted extraction to be a faster and more effective alternative to other methods. These studies also showed that fucoidan yield could be significantly increased by ultrasound-assisted extraction, while the extraction time was reduced [24]. Dwijayanto et al. (2025) compared the structural features and extraction performance of fucoidan from Sargassum sp. using conventional, microwave and ultrasonic extraction methods. The results showed that ultrasonic-assisted extraction had the highest yield as shown in (Table 1). The results of this study also showed that the use of ultrasonic bath method produced 2.5 times more fucoidan than the conventional method. Because ultrasonic waves have a cavitation effect that can improve cell wall lysis and solvent penetration by reducing mass transfer resistance and increasing polysaccharide diffusion, fucoidan produced by all three methods showed moderate antioxidant activity [31].

Table 1. Fucoidan extraction yields obtained using the conventional, microwave and ultrasound-assisted extraction methods

Parameter	Conventional	Microwave	Ultrasound
Extraction yield (%)	2.399±0.248	2.494±0.004	2.772±0.154

A study conducted by Antonisamy et al. in 2024 investigated the effect of extraction methods on the structural properties of fucoidan. The results showed that ultrasonic extraction reduced the total phenolic content and protein contamination and improved the purity of fucoidan. The extraction method used did not significantly affect the carbohydrate content of the extracted fucoidan. The thermal stability of fucoidan from S. ilicifolium indicates its potential industrial applications. The amorphous nature and enhanced solubility of fucoidan extracted by ultrasonic bath have strong application in drug delivery. The lower IC50 values observed for fucoidan obtained via ultrasonic bath method indicate higher potency in combating oxidative stress, inflammation and cancer cell proliferation. These findings indicate that the extraction method plays an important role in determining the bioactivity of fucoidan. In general, the integration of ultrasonic extraction with other green extraction technologies makes this method suitable for industrial-scale extraction of bioactive compounds from various sources [32].

3.2. Microwave-assisted extraction (MAE)

Conventional polysaccharide extraction (CE) is generally carried out with water, dilute acid or dilute alkali or enzyme-assisted extraction (disruption of plant cell wall components, such as cellulose, hemicellulose and pectin) for long periods of time at high temperatures and using large solvent volumes, and is therefore not economically and environmentally sustainable [33]. To overcome these limitations, advanced technologies such as microwave-assisted extraction use energy for heating and are a faster and more efficient method, increasing the mass transfer rate of solutes from the sample matrix to the solvent. In fact, open-tank microwave systems under atmospheric pressure can operate at a maximum temperature determined by the boiling point of the solvents. This type of extraction is based on electromagnetic waves that result in a distributed heat source that enhances cell wall disruption and fucoidan release into the aqueous extraction solvent [34]. This method has successfully extracted a variety of bioactive compounds from brown algae, including fucoidans and polyphenols, and the reduction in extraction time associated with MAE is consistent with energy conservation principles, making it an environmentally friendly alternative to conventional methods. MAE involves a combination of thermal and non-thermal effects that act synergistically to enhance the extraction of bioactive compounds from plant materials, including brown algae [35]. The primary mechanisms involved in microwave extraction include thermal effects, in that when microwave energy is applied, it causes rapid and uniform heating of the solvent and sample matrix. This localized heating results in an increase in temperature in the matrix, which in turn increases the solubility and release of bioactive compounds. Increasing temperature can weaken cell walls, facilitating the release of compounds into the extraction solvent [36]. A further effect is non-thermal effects (dielectric heating), in which microwave radiation also interacts with polar molecules within the sample matrix, causing molecular rotation and frictional heating. This phenomenon, known as dielectric heating, leads to rapid internal heating of the matrix itself. Non-polar compounds, such as lipids and essential oils, are extracted more efficiently due to the selective heating of polar components (such as water) in the matrix. This non-thermal effect contributes to efficient extraction by disrupting cell structures and promoting the release of bioactive compounds. Another effect associated with microwave extraction is the formation of voids and microbubbles in the solvent. As microwave radiation heats the solvent, evaporation can also occur, resulting in the formation and subsequent collapse of microbubbles [37].

MAE is a novel cell disruption technique in which microwave radiation, at a frequency of 300 MHz to 300 GHz, is generated by an electric field and a magnetic field that oscillate perpendicularly. Efficient microwave internal heating is achieved by converting electromagnetic energy into heat by two main mechanisms, dielectric polarization and ionic conduction [38]. Ionic conduction generates heat due to the resistance of the medium to the flow of ions when an electric field is applied. MAE technology has advantages over conventional extraction methods such as higher reproducibility, shorter purification times, and lower solvent and energy consumption, so MAE can be used for the extraction of proteins, carbohydrates, and polyphenols [39]. In the MAE heating system, microwaves are absorbed by the samples and converted into thermal energy that heats the moisture of the cells (Figure 2). Therefore, it may not be suitable for the extraction of heat-sensitive bioactive compounds. Depending on the configuration (open or closed), the intensity of the process varies. While open vessels operate at atmospheric pressure, closed vessels are used under pressurized conditions and at higher temperatures, the physicochemical properties of the water corresponding to subcritical conditions. Open vessel microwaves offer a highly efficient and controllable alternative to convective heating, but operation in closed equipment allows for better disruption of the cell wall assembly while preserving the fucoidan structure [40].

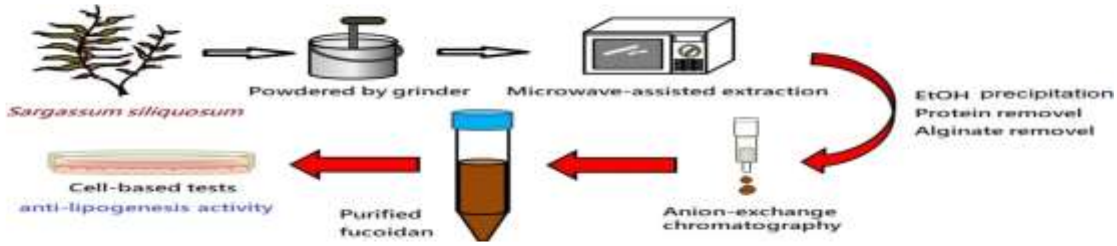

Fig 2. Preparation of fucoidan from brown algae by microwave method

In general, the efficiency of microwave heating depends on the dielectric properties of the material and its ability to absorb microwave energy and dissipate heat. Therefore, to evaluate the effect of MAE treatment temperature and time on the protein extraction yield from U. pinnatifda seaweed waste, it is better to use a lower temperature range [41]. The microwave-assisted extraction method has a short extraction time and hence reduces the cost compared to other conventional extraction techniques. In addition, MAE can be considered as an environmentally friendly technique due to its lower energy consumption [19]. In a study conducted by Chizuru Sasaki et al. in 2024, protein and sulfated polysaccharide fucoidan were efficiently extracted from brown seaweed waste (wakame) using the MAE method. The effect of extraction temperature and time on protein and fucoidan yield and finally, the continuous extraction of proteins and fucoidan were also investigated based on the extraction conditions. The results of this study showed that the continuous MAE method can extract bioactive proteins, water-soluble components (proteins and peptides) and fucoidan from the brown seaweed waste U. pinnatifda faster than conventional thermal extraction methods. [38].

In a study conducted by Ahmed Zayed et al. in 2023, they used microwave-assisted extraction (MAE) as a green method to extract fucoidan from different brown seaweeds, including Fucus vesiculosus, F. spiralis and Laminaria saccharina. Using the same extraction conditions, the chemical characterization revealed the heterogeneity of fucoidans among the brown seaweed orders, namely Fucales and Laminariales, where fucoidan derived from L. saccharina showed different characteristics in terms of higher sugar content and lower fucoidan content, in addition to a lower sulfate pattern and unique sulfate degree. However, MAE resulted in lower molecular weight products compared to classical solvent extraction and other green extraction methods such as EAE. Pre-treatment steps were successful to remove potentially extracted bioactive compounds that might interfere with fucoidan bioassay [40]. In a study by Wang et al. in 2021, fucoidan was extracted from a brown macroalga (Sargassum siliquosum) using microwave-assisted extraction (MAE) and ultrasound-assisted extraction (UAE). The results showed a higher extraction efficiency when using the MAE method under the conditions of 750 W, 10 min, and a liquid-to-solid ratio of 15 mL/g, with a total sugar yield of 94.6% on a dry weight basis. Based on the sugar and sulfate groups (the main components of fucoidan), the purity of the final sulfated polysaccharide product was close to 0.84%, and this purified fucoidan product showed biological activities related to anti-lipogenesis with a 28.9% reduction in lipid synthesis compared to the free-acid control [24].Quitain et al. (2013) conducted a study titled Microwave-hydrothermal extraction and decomposition of fucoidan from supercritical carbon dioxide deoiling of Undaria pinnatifida. They investigated how MAE affects the decomposition of fucoidan into low molecular weight compounds. The results showed that some biological activities, such as the antiproliferative activity of fucoidan, depended on the molecular weight of the fucoidan fractions. Polysaccharides with lower molecular weight showed higher antiproliferative activity, and products with higher sulfate content showed stronger antioxidant activity [42].

3.3. Pressure-assisted extraction (PLE)

Pressure-assisted liquid extraction (PLE) is a relatively new automated extraction technique that uses high pressure [43]. In pressure-assisted extraction, high pressure is used to maintain the solvent liquid above its normal boiling point and high temperature to extract compounds from samples in an oxygen- and light-free environment, in a short time and with less solvent, and high pressure keeps the solvent below its boiling point, thus allowing the application of temperatures above the solvent boiling point (at atmospheric pressure) [44]. This method can improve the extraction rate and yield by increasing solubility and mass transfer. Among the various solvents tested for the pressurized liquid extraction of Saccharina japonica (80–200 °C, 5–100 bar), sodium hydroxide gave the best yield of crude fucoidan. Hot water extraction under pressure is a special case of pressurized liquid extraction when water is used as the solvent [45]. This technology offers operational and environmental advantages due to the use of water and no chemicals, and offers a convenient, cost-effective and environmentally safe alternative compared to other methods. Extraction is facilitated by reducing extraction time and solvent requirements [46], it is more efficient for the extraction and polymerization of polysaccharides, and the method is carried out in an oxygen- and light-free environment, thus preserving the bioactives. Pressurized liquid extraction significantly improved the extraction yield of Himanthalia elongata fucoidans using an accelerated extraction solvent with water as the solvent by 103 times [47]. Dobrinˇci´c et al. in 2021 conducted a study to extract polysaccharides from brown algae F. virsoides and C. barbata by MAE and PLE methods. The results of this study showed that advanced extraction techniques, namely MAE and PLE, were successfully used and optimized to extract sulfated polysaccharides from brown algae F. virsoides and C. barbata. Although advanced extraction techniques did not improve the polysaccharide yield excessively, it was shown that the extraction time was reduced from 3 h to 30 min (PLE) or 10 min (MAE), which contributed to significant energy savings. In addition, polysaccharides obtained by PLE had the highest PDI, fucose, and sulfate group contents and the lowest uronic acid content. These findings suggest that

PLE and MAE can be effectively used as a potential method for extracting polysaccharides from brown seaweeds [33]. The pressure-assisted extraction method had environmentally friendly extraction systems and solvents, less extraction discrimination, and shorter extraction times. Emerging studies have observed that using this method yields much higher fucoidans and is an environmentally friendly extraction method, and solvent systems have less extraction discrimination, and shorter extraction times, providing a scientific basis for the industrialization of fucoidan production and extraction [48].

3.4. Enzyme-assisted extraction (EAE)

The use of enzymatic extraction for seaweed polysaccharides is an attractive option, attributed to the unique properties and advantages of enzymes. Enzymes can catalyze reactions with high specificity, they operate in a mild aqueous environment that can preserve the quality of extracts and fucoidan, EAE has great potential for industrial applications because it is easily scalable [10]. A large part of the polysaccharides of seaweeds are accumulated in the cell wall, which is associated with proteins and other polysaccharides. Enzymes have the ability to disrupt the cell wall and associated proteins, which in turn allows easier access to the solvent and solubilization of compounds from the cell wall. Various commercial enzymes have been used to extract polysaccharides from seaweeds [9]. Despite the great advantages of using enzymatic extraction, their application is limited by the high cost of enzymes, long extraction times, and limited opportunities for enzyme recovery. On the other hand, no enzyme has been specifically identified for the hydrolysis and extraction of seaweeds [49].

In 2023, Mapholi et al. investigated the potential of ultrasound-assisted enzymatic extraction (UAEE) for the extraction of fucoidan from Ecklonia maxima. The results of this study showed that ultrasound-assisted enzymatic extraction outperformed enzyme-assisted extraction and ultrasound-assisted extraction in terms of total carbohydrate yield, showing a 20% increase after 240 min [50]. In a study conducted by Shiying Tang et al. in 2022, enzyme-assisted extraction of fucoidan from Kjellmaniella crassifolia was investigated based on a kinetic study of enzymatic hydrolysis of algal cellulose. The results of this study showed that enzyme-assisted extraction was superior to hot water extraction in terms of yield and product purity. Under optimal conditions, the yield of fucoidan and the total sugar content and sulfate content reached 74.4% and 99.51%, respectively. In particular, the extracted fucoidan had a significantly high level of sulfate, which is associated with certain biological activities of fucoidan, and the product showed significant and concentration-dependent antioxidant activity [51].

3.5. Deep eutectic solvents (DESs)

Deep eutectic solvents (DESs)[8] are compositions made from a eutectic mixture of Brønsted–Lewis bases and acids, which have various types of cationic or anionic groups. DESs are classified as a type of ionic liquid due to their specific properties. They can be integrated with one or more complexes in the form of mixtures to form a eutectic function with a melting point lower than a specific compound [52]. DESs are advantageous because they contain non-toxic quaternary ammonium salts and are biodegradable and inexpensive. In addition, they have several properties such as low volatility, low melting point and high thermal stability, and also do not require purification steps, are made from low-cost compounds, have little or no toxicity, are biodegradable and can be easily recycled. Recently, DES have been used in several applications such as organic synthesis, catalysis, extraction media, enzymatic reactions, electron deposition and chromatography [53]. One of the main features of DES is their ability to be used as extraction solvents for a wide range of different chemical solutes, their application as solvents in extraction processes depends on their physical properties such as viscosity, density, miscibility

8 -Deep eutectic solvent

and polarity. It is convenient to choose solvents with low viscosity to facilitate mixing but with a high density difference from the matrix to facilitate phase separation [54]. In a study conducted by Saravana et al. in 2018, deep eutectic solvent was investigated along with subcritical water extraction of seaweed polysaccharides from Saccharina japonica. In this regard, a deep eutectic solvent was added with sufficient amount of water and used as the extraction medium. FTIR, TGA[9] and DSC[10] measurements confirmed that the extracted polysaccharides had alginate and fucoidan characteristics, and the crude polysaccharides showed moderate antioxidant activity. It was also shown that the fucoidan monosaccharides had a rich fucose content. Therefore, this process was shown to be a clean, rapid and efficient extraction process that improved the yield of polysaccharides from seaweed materials [55]. In a study by Kyle James et al. in 2024, which aimed to compare the sequential extraction technology of fucoidan and sodium alginate from Ascophyllum nodosum using glycerol and choline chloride solvents, they found that the fucoidan extracted through this extraction process with DES solvent in water contained up to 39% glycerol by weight. If the residual solvents in crudely extracted alginate and fucoidan are used as a combined bioactive component and plasticizer for alginate polymers, the combined solvent extraction method can be used as a low-cost food storage polymer [56].

4- Application of fucoidan in the food industry

Brown algae have been part of the human diet for hundreds of years, and in recent years, due to the increasing demand for a healthy diet and the search for alternative sources, commercial and scientific interest in brown algae has increased [57]. About 85% of the global production of macroalgae is food products for human consumption [58]. Only two macroalgal products have been authorized by the European Union as novel foods for use in food and food supplements: fucoidan extracts from F. vesiculosus and U. pinnatifida, and phlorotannins extracted from the brown algae E. cava. Fucoidans are also found in edible species such as L. japonica and C. okamuranus [59]. Fucoidans are very useful in the food industry due to their advantages such as low toxicity and high oral bioavailability. The lack of toxicity combined with bacteriostatic properties also allows their use in the food industry, increases the shelf life of the products and does not destroy the natural human microflora when ingested [60]. Some researchers studied the effect of adding algae to meat products, the results of the studies showed that the addition of algae improves the nutritional profile of meat products and increases the mineral content, dietary fiber and antioxidant compounds with improving the nutritional profile of meat products. At the end of the storage period, the authors reported that algae protect against oxidation reactions by reducing aldehydes, hydrocarbons, ketones and alcohols [61]. Studies have also shown that the addition of brown algae to bakery products improves their nutritional properties, texture, and antioxidant capacity, as they increase the mineral and dietary fiber content [62]. Pueda-Castillo et al. (2018) investigated the specific bioactivity of fucoidan, a compound isolated from Fucus vesiculosus, as a preservative in a pasteurized beverage marketed in the refrigerator. The results showed that fucoidan acts as a natural antimicrobial against Listeria monocytogenes and Salmonella typhimurium, opening new opportunities for the use of this natural compound as a bioactive ingredient for food preservation [63]. In general, fucoidan-based beverages can be used to modulate the gut microbiota to improve health. It has been reported that food processing reduces the concentration of fucoidan in the final product [64].

Another study also found that bread enriched with fucoidan had a higher volume, softer crumb, and biological activity (antioxidant and anticancer) after baking compared to the control group. In addition, bread enriched with fucoidan showed a reduced glycemic index compared to control bread. Laboratory analysis

9 -Thermal Gravimetry Analysis

10 -Differential Scanning Calorimetry

showed that the fucoidan in bread is highly bioavailable (i.e., from 1.77 to 8.79%) in the gastrointestinal tract [64]. Another application of fucoidan in the food industry is its use in emulsions. Emulsions refer to a mixture of immiscible liquids containing an oil and water phase that is used to deliver hydrophobic and hydrophilic bioactive compounds. A typical emulsion contains oil, water, and a surfactant. To design fucoidan-based emulsions, fucoidan acts as a surfactant or emulsifier [65]. Various studies have proven the emulsifying ability of fucoidans in emulsions. Fucoidans are used in oil-in-water, water-in-oil, water-in-oil-water and oil-in-water-oil emulsions. Fucoidans can be used to produce various emulsions such as nanoemulsions, multilayer emulsions, multiple emulsions and Pickering emulsions. Nanoemulsions are transparent and kinetically stable systems consisting of oil, water and an emulsifier [66]. Oliyaei et al. compared nanoemulsions prepared from different levels (0.5%, 1% and 2%) of fucoidan, gum arabic and sodium caseinate as emulsifiers with Tween 80, their results showed that increasing the concentration of emulsifiers caused a decrease in droplet size. Furthermore, the nanoemulsion containing Tween 80 was stable for 15 days, and the nanoemulsion of sodium caseinate, fucoidan, and gum arabic showed high stability [67]. Seaweed-derived films can be used as coatings on fruits, vegetables, and other perishable foods to extend their shelf life, reduce moisture loss, and prevent microbial spoilage. These coatings can also be formulated as active food packaging to deliver bioactive compounds such as antioxidants or antimicrobials, enhancing the nutritional value and safety of the food product [68].

Yusi Lan et al. (2024) prepared fucoidan-based coatings and evaluated their effects on the shelf life of nectarine fruit. The results showed that the use of fucoidan coating as a dense preservative layer on the surface of fruits can have positive effects such as significantly reducing transpiration, respiratory metabolism, weight loss and spoilage during storage at room temperature (20°C with 80% humidity), and also helps to reduce the loss of fruit nutrients, thereby improving the overall storage quality, taste and aroma of nectarine fruits [69]. Wang et al. (2014) in their study mixed fucoidan with chitosan and added anthocyanins extracted from the leaves of Coleus grass (Plectranthus scutellarioides). The results of this study showed that the addition of fucoidan in the chitosan matrix resulted in a decrease in WVP and OP values, tensile strength and elongation at break. On the other hand, the extract combined with fucoidan had high antimicrobial and antioxidant activity and was able to detect salmon spoilage during storage [70]. Malekkolaei et al. (2025) conducted a study aimed at evaluating the effectiveness of composite edible coatings made of chitosan and fucoidan in combination with carp (Carassius carassius) protein hydrolysate (CPH). The results showed that at higher concentrations, these compounds significantly improved the chemical and microbiological properties of the fillets. As a result, it was found that composite edible coatings containing chitosan and fucoidan, together with hydrolyzed nanoproteins from carp, effectively increased the shelf life and quality of fish fillets. These findings emphasize the high potential of these edible coatings in maintaining the quality and safety of seafood products [71]. A study by Bing Xu et al. (2021) aimed at investigating the effects of fucoidan coatings on the shelf life of mango fruits was carried out. In this study, fucoidan coatings with different concentrations (1, 3, and 5%) were evaluated to increase the shelf life of mango fruits at room temperature (20°C, 80% humidity). The results showed that the coatings containing the highest fucoidan concentration exhibited the greatest protective effects. Considering that mango fruits are aerobically respiring fruits, the results showed that fucoidan coatings with high doses were able to delay the respiratory peak by up to three days, thus effectively extending the shelf life of mango fruits [72]. In 2018, Luo et al. used extracted fucoidan as a natural antioxidant in Chinese-style sausages during storage at 4°C for 18 days. Compared with the control samples, fucoidan sausages showed less changes in pH, brightness, redness, yellowness, and sensory properties [73]. Ping Luo et al. (2020) conducted a study titled Effect of Fucoidan-Based Edible Coating on the Kinetics of Antioxidant Degradation of Strawberry Fruit

During Cold Storage. They investigated the effect of fucoidan from Laminaria japonica (FL) on post-harvest freshness of strawberries. The results showed that FL coating effectively reduced the incidence of decay and the decline of endogenous antioxidant capacity, and prolonged the shelf life of strawberries in the refrigerator at 4 °C. Overall, this study proved that FL is a natural freshness agent for fruits and vegetables after harvest [74].

5. Advantages and Limitations of Green Extraction Methods

In general, all purification and extraction methods, conventional or green, of fucoidan, which are fully summarized in (Table 2), have advantages and disadvantages. The selection of the extraction process should consider the recovery rate, cost, time, solvent volume, and scale-up. Under suitable conditions, water extraction is the simplest method for extracting polysaccharides from plants, microbes, and algae. However, high temperatures and extended processing times may destroy polysaccharides and important bioactive chemicals. In contrast, green extraction methods can successfully extract polysaccharides with short treatment times, low solvent consumption, high extraction yields, and other rich features [75].

Table 2. Extraction and purification of fucoidans

Species	Extraction method	Extraction conditions	Purification	Yield (%)	References
F. evanescens	Enzyme-assisted extraction	Cellulase and alginate lyase was added to the seaweed at 40 ◦C and pH adjusted to 6 for 24 h.	Anion-exchange chromatography using DEAE-Macroprep resin material.	18.2	[77]
A. nodosum	Enzyme-assisted extraction	Cellulase and β-glucanase was added to the seaweed at 50 ◦C and pH adjusted to 6 for 3 h	Ultrafiltration using a membrane of 100 kDa.	23.41	[78]
S. latissimi and Alaria esculenta	Enzyme-assisted extraction	cellulase blend Cellic® Ctec2 along with endo- (AMOR-PL7) and exo-acting (AMOR-PL17) alginate lyases was added to seaweeds at different ratios for 24 h (55 ◦C)	Not required as purified fucoidan was obtained	8-12 (S. latissimi) and 4–15 (A. esculenta)	[79]
N. zanardinii	Enzyme-assisted extraction	Alcalase was added to the seaweed at 50 ◦C and pH adjusted to 8 for 24 h. Viscozyme was added to the seaweed at 50 ◦C and pH adjusted 4.5 for 24 h	Dialysis of membrane 8.0 kDa.	4.28–5.58	[80]
F. virsoides	Microwaveassisted extraction	Irradiation of seaweed in a microwave vessel at 80 ◦C for 2 min	Ethanol precipitation	13.19	[81]
A. nodosum	Microwaveassisted extraction	Irradiation in a microwave reactor at 120 psi for 1 min.	Ethanol precipitation	14.02	[19]
S. muticum	Ultrasoundassisted extraction	Extraction in an ultrasonic bath at room temperature with intensity 1.5A, 40Hz	Ethanol precipitation followed by size exclusion chromatography.	4.60	[26]

		and power 150W for 5–30mins.			
A. nodosum	Ultrasoundassisted extraction	Use of sonicator probe of power 750W, and frequency 20 kHz	Dialysis of membrane size 14 kDa	NR	[82]
Sargassum henslowianum C. Agardh.	Hot-water-assisted ultrasound extraction	Ultrasonicated at 350 W at 60 ◦C for 45 min. The solution was further extracted in a water bath (80 ◦C) for 3.5 h	DEAE cellulose 52 column (2.6 × 80 cm) step elution with different concentrations of NaCl	6.25	[83]
C. barbata	Pressurized liquid extraction	Extraction in accelerated solvent extractor of pressure 1500 psi, and a temperature of 100 ◦C for 5min.	Ethanol precipitation	6.43	[81]

Microwave-assisted extraction (MAE) is a short-time extraction method that can be performed with both organic and aqueous solvents, making it a suitable method for heat-sensitive chemicals and more practical than the traditional Soxhlet process. Only solvents with high dielectric constants and low dissipation factors are suitable for this method. The MAE method has a significant explosion risk. Microwave-assisted extraction and supercritical fluid extraction methods, despite reducing extraction time, require high investment, while enzyme-assisted extraction methods also face the challenge of selecting the right enzyme. In ultrasound-assisted extraction, the extraction efficiency depends on the composition of the plant matrix. Preferred solvents for ultrasound are those with low surface tension, viscosity, and vapor pressure. Excessive use of sonication can potentially compromise the quality of the extracts [84]. Supercritical fluid extraction (SFE) is a form of green extraction. The extracts obtained by this method are of high purity and free from any contaminants. The extracts obtained without the use of solvents and with minimal extraction time are an ideal method for the extraction of heat-sensitive compounds, however, this method has disadvantages such as expensive equipment for high pressure applications. The extraction of polar molecules may have challenges such as high processing costs and energy consumption. In general, the green extraction method is expensive due to high processing costs and energy consumption. However, it offers efficient extraction with good yield and requires less time [85]. The disadvantages and advantages of fucoidan extraction methods are listed in Table 3.

Table 3. Advantages and disadvantages of fucoidan extraction methods

Disadvantages	benefits	Extraction methods
Low yield, extraction of unwanted compounds	Simple, safe, no chemicals required	**hot water**
Structural change, reduction in biological activities	Increase efficiency	**dilute acid**
High cost	Maintaining the structure of phycocyanin, environmentally friendly	**enzymatic**
Need for special equipment	Increase efficiency, reduce time	**ultrasound**
High cost, requires additional purification	Improve purity	**organic solvents**
Need for precise control of conditions	High speed, increased efficiency	**Microwave**

6-Conclusions

Large algae contain bioactive compounds with various applications in the food, cosmetic and pharmaceutical industries. They showed potential for the development of new functional products that could have a positive impact on human health. Alternative modern green extraction techniques for fucoidan extraction from brown algae were presented in this review, methods such as SFE, UAE, SWE and MAE can be used to isolate specific bioactive compounds such as fucoidan. Green extraction methods are mostly used for the extraction of bioactive compounds, these methods are environmentally friendly, time-saving and produce high yields. Seaweeds contain antioxidants that reduce lipid oxidation, thereby increasing the shelf life and nutritional value of food and reduce free radicals and delay bacterial growth. The main advantage of these methods is that the extraction of target compounds and their solubility can be controlled by the applied process parameters of each method. Recent advances in seaweed bioactive compounds have improved food packaging quality and functional properties, and have increased innovation and sustainability in food production. Their natural origin, biodegradability, and potential for incorporating functional properties make them attractive options for the food industry. Seaweed compounds are a good source of gelling, thickening, and emulsifying agents in food products. Seaweed-based films have shown excellent performance in sustainable packaging for fresh produce, seafood, bakery, and confectionery products. Overall results indicated that seaweed-based food packaging materials are promising and sustainable alternatives to traditional plastic packaging.

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Author Contribution

Parisa Lotfi: Validation, Investigation, Resources, Data Curation, Writing – Review and Editing.
Sajad Pirsa: Conceptualization, Methodology, Writing – Review and Editing, Project Administration.

Ethics Statement

The research was conducted in full accordance with established ethical principles. All participants were engaged voluntarily after being thoroughly informed about the study's objectives and procedures. Informed consent (written or verbal) was obtained from each participant, their data were handled with strict confidentiality, and they retained the right to withdraw from the study at any point without consequence.

Conflict of Interest

All 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.

Data Availability

The datasets generated and/or analyzed during the current study are not publicly available due to privacy considerations but are available from the corresponding author upon reasonable request.

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استخراج فوکوئیدان از جلبک قهوه‌ای و کاربرد آن در صنایع غذایی

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چکیده

فوکوئیدان یک پلی ساکارید سولفاته از جلبک دریایی قهوه‌ای متشکل از چندین مونوساکارید است که در دیواره سلولی جلبک دریایی قهوه‌ای یافت می‌شود و از سلولز مقاوم و همی سلولز تشکیل شده است. این ترکیب فعال زیستی دارای چندین خواص زیست فعال مانند آنتی اکسیدانی، ضدمیکروبی، ضدویروس، کاهنده چربی خون، ضدسرطان و تومور زایی، ضد التهاب وتعدیل کننده سیستم ایمنی است. آن‌ها به دلیل طبیعی بودن و عملا غیر سمی بودن، به عنوان یک جز ضدمیکروبی امیدوارکننده برای کاربردهای مختلف در پزشکی و صنایع غذایی در نظر گرفته می‌شوند. خواص فوکوئیدان به عوامل متعددی از جمله وزن مولکولی و روش استخراج بستگی دارد که وزن مولکولی فوکوئیدان، مرتبط با فعالیت‌های بیولوژیکی و فراهمی زیستی آن، می‌تواند تحت تأثیر فن‌آوری‌های استخراج قرار گیرد که طیف گسترده‌ای از روش‌های استخراج در حال حاضر برای به دست آوردن این پلی‌ساکاریدها استفاده می‌شود، مانند استخراج مایع فوق بحرانی (SFE)، استخراج مایع تحت فشار (PLE)، استخراج آب زیربحرانی (SCWE)، استخراج به کمک اولتراسوند (UAE)، استخراج به کمک آنزیم (EAE) و استخراج به کمک مایکروویو (MAE)، باتوجه به اینکه تعداد فزاینده‌ای از تحقیقات در چند سال گذشته روند استخراج فوکوئیدان را نشان داده است و استفاده از ترکیب فوکوئیدان یک استراتژی موثر در توسعه فیلم‌های زیست فعال در پوشش‌های غذایی است که سبب کاهش اتکا به مواد پلاستیکی و افزایش ماندگاری محصولات غذایی خواهد شد. این بررسی فرآیندهای مرسوم استخراج و خالص سازی، فعالیت‌های فیزیکو شیمیایی و بیولوژیکی و خصوصیات ساختار و پیشرفت‌های اخیر کاربرد فوکوئیدان در صنعت غذا را ارائه می‌دهد.