Discover Food

Review

Seaweed organic compounds source of hydrocolloids and sustainable food packaging: properties, application, and future direction

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Abstract

Seaweed has different biologically active macromolecules, including polyphenols, fiber, proteins, and polysaccharides. Recent developments in seaweed bioactive compounds improved food packaging quality and functional properties and increased food production innovations and sustainability. Seaweed compounds are a good source of gelling, thickening, and emulsifying agents in food industrial products. Further Green Extraction methods are used for the extraction of bioactive compounds, these methods are environment friendly, with less time and high-yield production. Seaweeds incorporate antioxidants that reduce lipid oxidation, thus enhancing food's durability and nutritional value and reducing free radicals' occurrence and retard the growth of bacteria. Seaweed has increased its potential for antimicrobial packaging solutions. The manuscript explores the perspective for advancing seaweed-based films, involving property improvements, increased shelf life, and production scalability. Seaweed-based films offer sustainable packaging for fresh produce, seafood, bakeries, and confectionery products. Seaweed-derived bioactive compounds enhance the quality and safety of packaged food products and seaweed polysaccharides in food packaging are their biodegradability and environmental friendliness.

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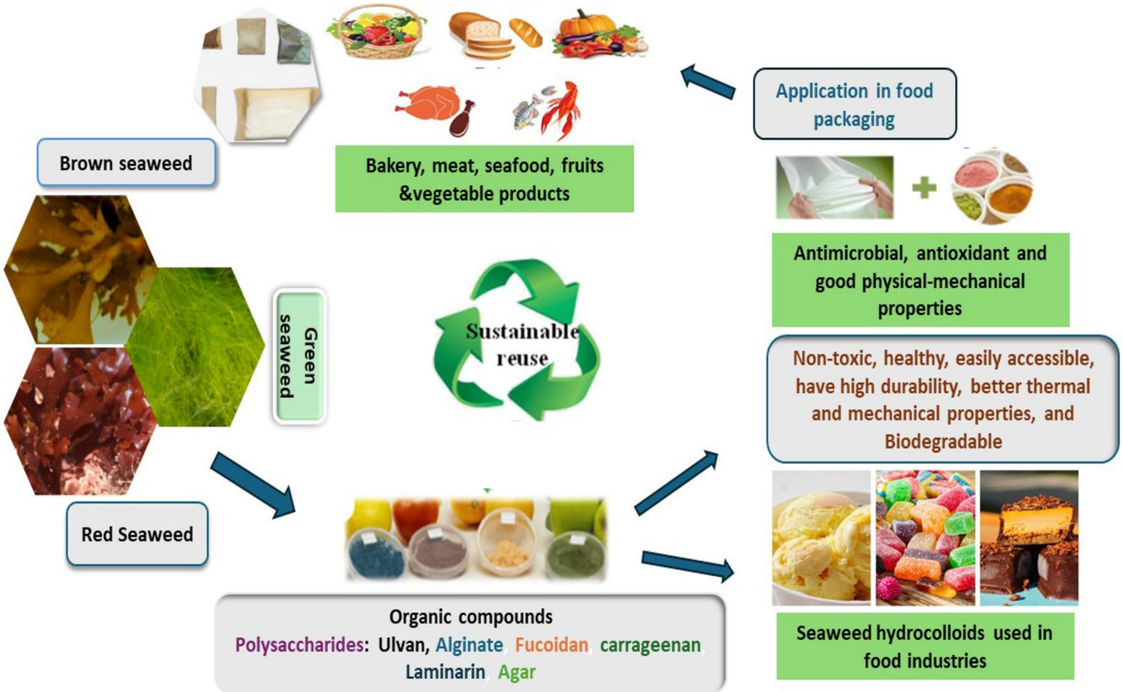
Graphical Abstract



Keywords Seaweeds · Bioactive compounds · Polysaccharides · Food packaging · Sustainable packaging

1 Introduction

The demand for sustainable packaging has surged due to environmental concerns like plastic pollution and climate change. The edible films and coatings offer functional and sustainable benefits, protect perishable products from moisture and contamination, and increase their shelf life. This approach addresses the global need for creative packaging solutions that minimize environmental effects [1].

Packaging is a significant component in food industries that helps the essential functions of preserving food and ensuring its overall quality and food safety [2, 3]. The importance of packaging within the broader supply chain framework is not without obstacles. These complications include the potential passage of waste products, cost-effectiveness and energy efficiency considerations, and the imperative of sustainability [4, 5].

Seaweed, rich in polysaccharides and other bioactive compounds, is an efficient source of food packaging materials. Combined with biodegradable polymers, the composite material provides a sustainable, eco-friendly alternative that outclasses packaging materials [6]. Biodegradable polymers, like polyhydroxy butyrate and polylactic acid, are made from renewable resources such as microbial polyesters, proteins, and polysaccharides. Biobased plastics, made from these materials, are particularly useful in food packaging applications like edible coatings and films because they have antimicrobial and antioxidant properties and polysaccharides for packaging that contribute to environmental preservation [2, 7]

Various industrial processes, mainly in the food industry, generate considerable seaweed waste and the significance of reusing these waste materials cannot be emphasized enough, as releasing them into the environment may adversely affect marine ecosystems. Furthermore, this movement underscores algae's immense potential for high-value products as a renewable energy source [8, 9].

Seaweed holds sustainable biomass with numerous possible applications. Research has indicated a high potential for seaweed use in various fields, including the food industry. However, further research is necessary to ensure the successful implementation of this potential [10–12]. Algae's biometabolites have various biological properties like antibacterial, anti-cancer, anti-fouling, anti-inflammatory, antimitotic, antiviral, and antibiotic [13, 14]. Recently, marine algae have been identified as a potential source of organic compounds that have advantageous effects on health. The quantity of these beneficial compounds is affected by various factors, such as water temperature, nutrients, and salt content, which control the growth conditions of marine algae [15, 16].

This article explores the use of seaweed polysaccharides in food packaging, highlighting their chemical, mechanical, antioxidant, and antimicrobial properties. Seaweed compounds are a good source of gelling, thickening, and emulsifying agents in food industrial products. The potential for advancements in seaweed-based films and the implications of their use in various food packaging scenarios, including seafood, bakeries, and fresh produce. The review also expects and provides future research pathways in seaweed-based films.

2 Overview of seaweeds

Seaweeds, benthic, macroscopic, and multicellular algae, exhibit greater photosynthesis efficiency than their terrestrial counterparts. Consequently, they grow faster, resulting in rapid biomass accumulation. Seaweed constitutes a significant proportion of marine biomass, contributing to approximately 50% of the earth's primary production. Their versatile applications, which include food and feed production, have made them extensively utilized [17]. The considerable abundance of seaweed has increased demand, leading to the widespread cultivation of this marine resource over the past decade. Seaweed farming and production processes have experienced significant expansion, playing a role in the biotechnological and fishing industries of nations [18]

Seaweed represents a critical living resource for marine biodiversity, with more than 10,000 species worldwide growing on firm substrates, including rocks at depths of up to 180 m. These species were classified into three groups: red (Rhodophyta), brown (Ochrophyta), and green (Chlorophyta) [19]. Seaweeds constitute an outstanding source of diverse bioactive compounds in several fields, including pharmaceuticals and agriculture. Different types of seaweed, red, green, and brown images are displayed in Fig. 1.

Red seaweed stands out from its unique red and blue pigments, namely phycocyanin, phycoerythrin, and chlorophyll a. The variety of red seaweed species is due to their diverse plant forms and life cycles. Prominent examples of red seaweed species are *Poryphyra capensis, Notogenia stiriata, and Aeodes orbitosa* [21].

Brown seaweed comprises many polysaccharides, including fucoidans, alginate, and laminarin. Brown seaweed exhibits various sizes, species, and overall morphologies. They are generally characterized by their brown colour, which is

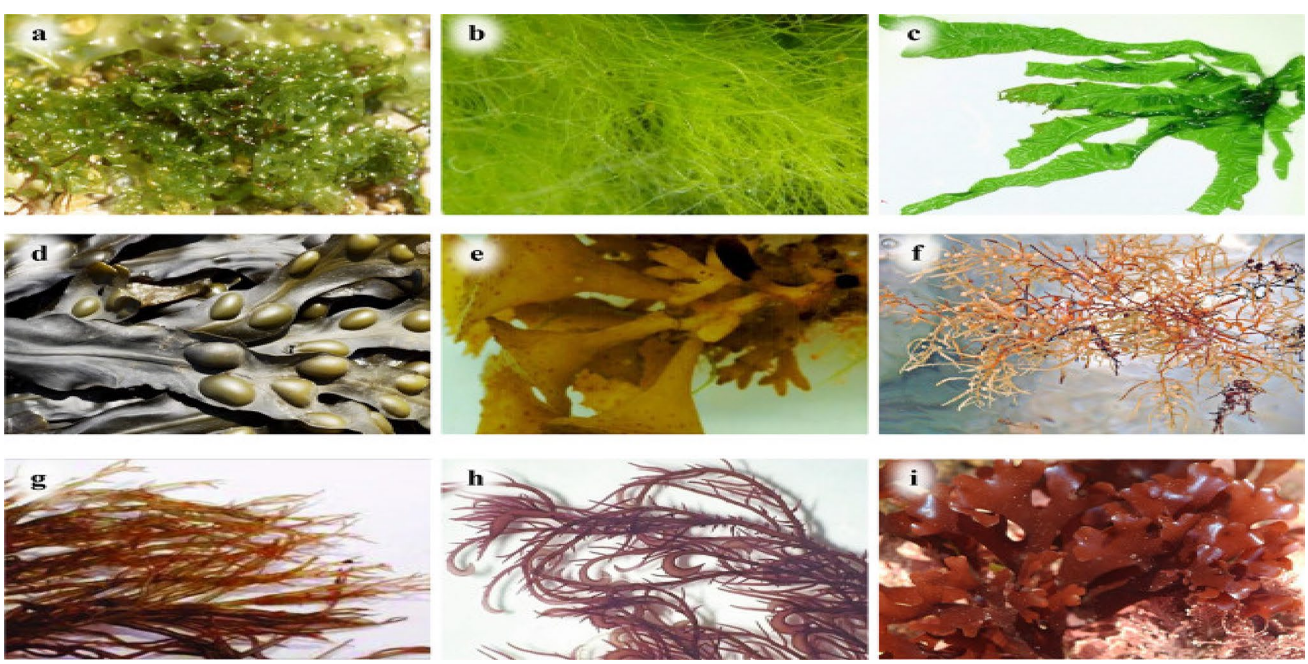


Fig. 1 Seaweeds as green, brown, and red. **a** *Ulva reticulata Forsskål*; **b** *Chaetomorpha linum Kützing*; **c** *Ulva lactuca f. fasciata*; **d** *Fucus vesiculosus Linnaeus*; **e** *Turbinaria turbinata Kuntze*; **f** *Sargassum natans Gaillon*; **g** *Gracilaria edulis*; **h** *Hypnea musciformis*; **i** *Chondrus crispus* [20]

attributed to the occurrence of a photosynthetic pigment called fucoxanthin. Kelp, including species such as *Laminaria pallida, foucus, and zonaria,* is a widespread type of brown seaweed [22].

Green algae are common in fresh and saltwater environments, and their green colour is due to chlorophyll a and b [23, 24]. Common green seaweed includes the genera Monostroma, Cladophora, Ulva, and Chaetomorpha species. These are commonly encountered in marine and brackish water environments. Chaetomorpha and Cladophora are filamentous green algae often found in intertidal areas, attached to rocks, or floating freely in the water [24, 25].

3 Extraction methods for bioactive components

Seaweed has been an excellent source of diverse bioactive compounds in several fields of food and pharmaceutical industries. For extraction of bioactive compounds from seaweeds in Conventional Extraction such as Solid–Liquid Extraction (SLE), this extraction uses organic solvent with a specified extraction time. The further efficient methods are Green Extraction methods, these methods are environment-friendly with high-yield productions. Green extraction processes such as Ultrasound-assisted extraction (UAE), Microwave-Assisted Extraction (MAE), Supercritical Fluid Extraction (SFE), and Reactive Extrusion Using a small amount of solvent under specific conditions with a fast extraction [26].

3.1 Ultrasound-assisted extraction (UAE)

Ultrasound-assisted extraction is more efficient than conventional extraction and some other green extractions. Ultrasound allows greater solvent penetration into the sample by increasing the contact surface between the solid and liquid phases [27]. Uses ultrasound waves with a frequency between (20 and 100) kHz which causes bubbles due to the created pressure difference. Then, these bubbles collapse and undergo cavitation, which causes the breakdown of the liquid–solid interface near the particles, releasing bioactive compounds into the substance [28].

The ability of ultrasound to stimulate cavitation depends on several factors including ultrasonic frequency and intensity, properties of the medium such as surface tension and viscosity and ambient conditions including temperature and pressure [29]. Ultrasound decreases extraction time, solvent used and processing costs [27]. Parameters that are optimized during this method are frequency, power, temperature, time and sample and solvent ratio [30]. The application of UAE in producing bioactive compounds from seaweed extraction such as phenolic compounds. Some main advantages of extracting phenolic compounds from seaweed using the UAE method are low temperature, short time and a small quantity of solvent [31].

Polysaccharide compounds in the form of *laminaria* obtained by the UAE method show better biological activity, and antioxidant and antimicrobial activity and preserve better antioxidant properties [32]. Another study shows that a high percentage of fucoxanthin and phenolic compounds from (*Padina tetrastromatica)* macroalga [33]. Using UAE for extraction of fucoidan from *Sargassum echinocarpum* gets a high yield (2.8–3.9%) and high antioxidant activity between (44.6–98.8 ppm) mostly depending upon the extraction conditions [34]. The research shows that UAE extraction methods are efficient for organic compounds. Seaweed (Sargassum carpophyllum) extract has a good total phenolic compound (46.22–65.00 mg) phloroglucinol, ethanol concentration is 50% and ultrasonic power was 200 watts [35].

3.2 Microwave-assisted extraction (MAE)

MAE is an alternative technology that provides an environmentally and economically advantageous option. It allows the production of affordable and high-quality compounds that meet "green" environmental criteria. This method is efficient due to the reduced processing time and amount of solvent used [36]. This technique integrates microwave and conventional solvent extraction, utilizing ionic conduction and dipole rotation to directly affect and occur simultaneously with the molecules [37]. Microwave heating induces energy absorption by polar molecules without any heat loss to the surroundings, while simultaneously disrupting cells. Damaged cells enhance the speed of mass transfer and diffusion out of a solid when the processes of mass and heat transfer work together and in the same direction [38]. Microwave extraction involves using microwave power to heat samples and solvents that are contained in high-quality vessels, with the temperature being carefully regulated [39].

The use of microwave-assisted pressurized hot water extraction (MAPHWE) technology for solubilizing seaweed components, specifically at an initial stage, has been explored in various studies. This method is recognized for its efficiency in extracting valuable compounds from seaweed, such as polysaccharides, phenolic compounds, and other bioactive substances while maintaining a green and sustainable approach [40]. A study shows that MAPHWE was applied to Rugulopteryx okamurae at 180 °C for 10 min with a liquid-to-solid ratio of 30, resulting in the dissolution of over the (40%) initial material. The alginate recovery yield was (3.2%) and the phenolic content of the water-soluble extracts was (2.3%). When distilled water was used as the solvent both were slightly higher. Interestingly, the carbohydrate content in the extract remained consistent at 60% regardless of the solvent used, while the sulphate concentration was higher in samples processed with salt water from the same coastline as the seaweed [41].

Ulva prolifera, a green alga, uses MAE technology to study polysaccharide characteristics and bioactivities. Temperature and acid concentration increased sulphur and decreased molecular weight. The extraction of polysaccharides at 90 °C with 0.05 M HCl is noted for its superior water-holding capacity (41.32 g/g) and oil-holding capacity (15.09 g/g). This suggests that the extraction conditions, including temperature and pH, significantly influence these properties. Regarding the foaming properties, the extraction at 150 °C with 0.05 M HCl is highlighted for its optimal foaming capacity (143% and 113%) and higher antioxidant activity [42]. A study shows that *Carpophyllum flexuosum, Carpophyllum plumosum,* and *Ecklonia radiata* brown seaweeds have strong antioxidant activity (62.1 mg gallic acid) and radical scavenging ability [43].

Figure 2 indicates that four kinds of brown algae, namely *Ascophyllum nodosum, Fucus vesiculosus, Laminaria digitata,* and *Saccharina latissima*, were utilized to extract organic compounds using three different pretreatment methods. Among these methods, swelling had the most stated impact on improving the production of bioactive compounds. By incorporating the UAE and MAE techniques in the processing of seaweed, the production of bioactive substances such as pigments, mannitol, and polyphenols can be increased. This has the potential to improve their abilities to combat free radicals and iron chelating capacity [44].

In this study most suitable conditions for solubilizing *Ascophyllum nodosum* seaweed biomass using microwave-assisted extraction were temperature (120 °C) and a solid-to-liquid ratio (1.03 w: v), a processing time (15 min). which maximized solubilization efficacy while minimizing the applied energy per mass of solubilized seaweed. Antimicrobial tests conducted on *S. aureus* and *E. coli* showed up to 97% inhibition of bacterial growth after 8 h, indicating the presence of antimicrobial characteristics in the extracts obtained through the dedicated microwave extraction of *Ascophyllum nodosum* [45].

3.3 Supercritical fluid extraction (SFE)

Applied generally at both laboratory and industrial levels, SFE is a green extraction process for important non-polar or mid-polar substances such as lipids, essential oils, and carotenoids [46]. Using solvents in the supercritical conditions of this method; so, temperature and pressure are elevated over their critical point. Under those conditions, supercritical

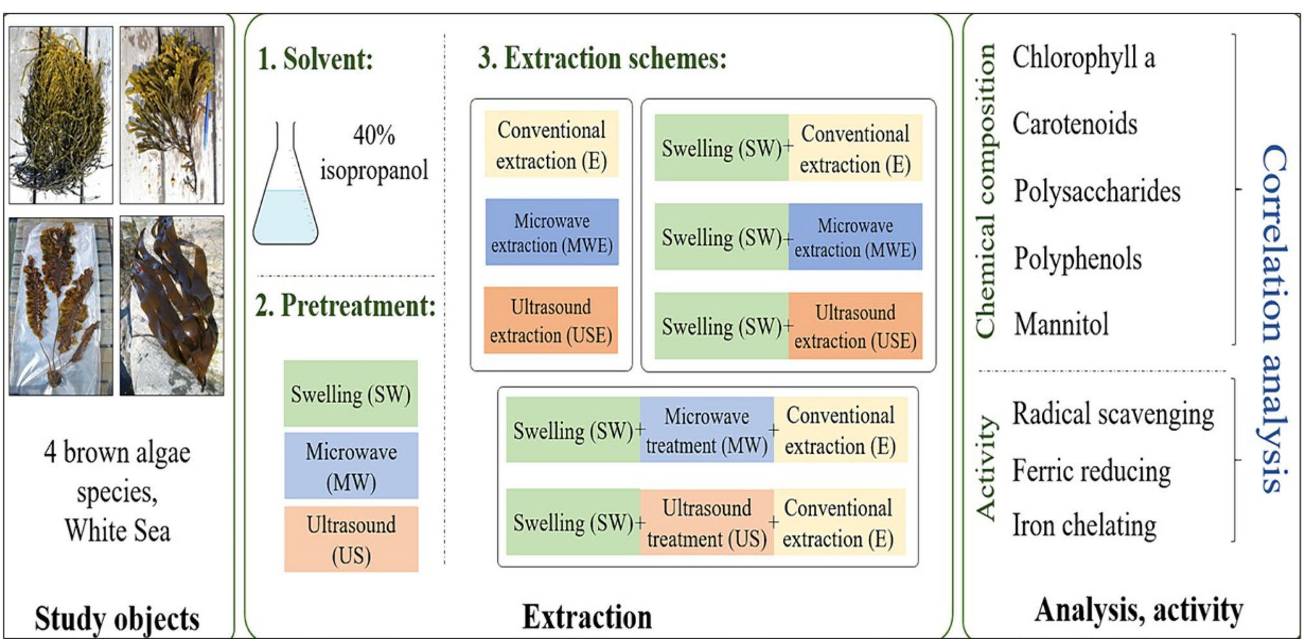


Fig. 2 shows the effects of extraction methods on chemical composition and bioactivity [44]

fluids often acquire higher density but keep similar viscosities and intermediate diffusivities to gas [47]. Carbon dioxide is the recommended solvent for the extraction of bioactive substances from natural sources since other fluids can be employed at supercritical conditions. Among its various benefits are mild critical conditions associated with carbon dioxide. It is cheap, safe, environmentally friendly, non-toxic, non-flammable, non-explosive, easily available [48].

Conditions during the extraction, especially pressure and temperature, influence the solubility and selectivity of the many chemicals in the supercritical fluid [47]. low critical temperature (31.1 °C) and pressure (73.8 bar), carbon dioxide is a great solvent for extracting heat-sensitive bioactive chemicals so preserving them, and no degradative changes can occur [47]. In addition to temperature, pressure, supercritical solvent, proportion, and type of co-solvent, various other factors are associated with and linked to the sample and the extraction process. These factors include water content, particle size, dispersant agent, sample amount, SCF flow rate, mode of extraction, extraction time, and fractionation [49]. The interactions of various components that enhance a specific process are complicated. Therefore, obtaining appropriate extraction conditions is important for the successful isolation of bioactive compounds [30].

The study examined the application of a design of experiment to assess supercritical fluid extraction (SFE) as a sustainable extraction technology. The approach utilized a mixture of CO2, ethanol, and water. The temperature was regularly varied between 40 and 80 °C while keeping the (300 bar) constant pressure [50]. Alaria esculenta, Laminaria digitata, and Ascophyllum nodosum seaweed were used for analysing organic compounds. The highest level of selectivity was achieved while employing CO2 with a concentration of only 5 vol% ethanol and no water. This facilitated a significant retrieval of β-carotene and yielded an extract devoid of carbohydrates, proteins, and toxic metals such as arsenic. The most effective methods for extracting the highest amount of the remaining target analytes showed considerable diversity. The analytes with the highest water content, including fucoxanthin and phloroglucinol, also had the lowest relative selectivity [50].

3.4 Advantages and limitations of green extraction methods

All extraction methods, conventional or green have advantages and disadvantages. An extraction process selection must consider their, rate of recovery, cost, time, solvent volume, and scale-up. Under suitable conditions, water extraction is the easiest approach for polysaccharide extraction from plants, microbes, and algae. However, high heat and extensive processing times may degrade polysaccharides and important bioactive chemicals [51]. In contrast, green extraction methods can successfully extract polysaccharides with short treatment time, low solvent consumption, high extraction yields, and other enriched features [52].

Microwave-assisted extraction (MAE) has a brief duration of treatment. Both organic solvents and water are viable options for application. Appropriate for heat-sensitive chemicals, and superior to the traditional Soxhlet process. Only solvents possessing a high dielectric constant and a low dissipation factor are suitable for application. The MAE closed vessel has a significant risk of explosion, particularly its high capital cost [39]. Ultrasound-assisted extraction (UAE) is characterised by a brief treatment duration and reduced solvent usage. Optimal extraction efficiency, Affordable. The effectiveness of extraction is contingent upon the composition of the plant matrix. Preferable solvents are those that have low surface tension, viscosity, and vapour pressure. Overusing sonication can potentially impair the quality of extracts [53].

Supercritical Fluid Extraction (SFE) is a form of green extraction method. Extracts obtained with high levels of purity and without any remaining contaminants. Extracts obtained without the use of solvents and with a minimal extraction duration are an ideal method for extracting thermolabile compounds, however, it does have some drawbacks. Expensive equipment is required for high-pressure applications. Extracting polar molecules may provide challenges. The processing cost and energy usage are high [54]. The green extraction technique is costly because of its high processing expenses and energy consumption. However, it offers efficient extraction with a good yield and requires less time [54–57].

4 Bioactive compounds in seaweed

As living marine resources, seaweed contains abundant macro- and micro-nutrients, including carbohydrates, proteins, fiber, vitamins, and minerals. They serve as natural sources of macro elements, including sodium, calcium, potassium, magnesium, Sulphur, chlorine, and phosphorus, as well as micro aspects like iodine, zinc, copper, selenium, nickel, cobalt, boron, and manganese. Seaweeds contain substantial amounts of iodine, which is crucial in preventing goiter disease in humans [58, 59]. Red and green seaweed generally exhibits a high protein content, up to 30%, as compared to brown seaweed. However, green seaweeds are typically rich in carbohydrates compared to red and brown seaweed [60].

The green seaweed *Ulva lactuca* and *Enteromorpha intestinalis* have the maximum amount of carbohydrates, i.e., 36.01% and 31.08% [61, 62], and brown seaweed (*Dictyota dichotoma*) contains minimum carbohydrate content, i.e., 09.95% [63]. The fiber content of seaweeds ranges from 35 to 60% of dry mass, higher than other plants [10, 58]. The lipid content of seaweed generally ranges from 5.1% in *Ulva clathrata* to 1.29% in Enteromorpha intestinalis. However, studies reported that lipid content in *Utricularia rigida* is 13% and *Kappaphycus alvarezii*, 1.07%, respectively [64, 65].

Various commercially available seaweed species, namely *Undaria pinnatifida*, *Saccharina angustata*, *Pyropia tenera and Sargassum fusiforme* along with nine non-commercial seaweed species, specifically *Ecklonia radiata, Cystophora polycystidea, Hormosira banksii, Codium galeatum, Durvillaea potatorum, Cystophora torulosa, Phyllotricha decipiens, Laurencia filiformis,Phyllospora comosa,* were examined by a group of researchers to determine their functional properties. The protein, total lipid, crude fiber, and ash content of commercially available seaweeds ranged from 32.76 to 350 mg/g, 7.24 to 31.5 mg/g, 28.85 to 46.24 mg/g, and 120.3 to 297.45 mg/g, respectively. In difference, the varieties of non-commercial seaweeds were found to be 31.5 to 157 mg/g, 4.57 to 102.05 mg/g, 31.32 to 219.96 mg/g, and 54.56 to 196.06 mg/g, respectively [66–69]. In addition, seaweeds are a rich source of Fat and water-soluble vitamins, phenolic compounds and essential fatty acids (ω-6 and ω-3 fatty acids), as reported in this study [70]. The bioactivity of the substances present in seaweeds is given in Table 1.

5 Seaweeds polysaccharides

Polysaccharides have different structures and properties, and it is a sulfated (e.g., fucoidans, carrageenans, Galatians, and agars) or non-sulfated (e.g., alginates and laminarin) [79, 80]. These polysaccharides are important in food packaging materials and increase their physical and functional properties. Table 2 shows different associated polysaccharides and their chemical structure. The main types of seaweed and their polysaccharides compounds are presented in Fig. 3.

5.1 Agar and Carrageenan

Sulfated galactans, including carrageenans and agar, are present in seaweeds and extensively utilized as biopolymers in the food industry [60]. Agar and carrageenan are digestible oligosaccharides that are harmless to human teeth and are linked with various beneficial properties, such as prebiotic effects, anti-tumor, antioxidant, and immune-modulating effects [19, 93].

Agar is comprised of agarose and agaropectin, which have structures and functions comparable to carrageenan. Its ability to gel, emulsify, and thicken makes it a valuable substance not just in scientific research but also in different commercial applications, including food and medical productions [59, 60, 94].

Carrageenan solubility is affected through its hydrophilic and anionic properties, with greater sulphate ester levels resulting in higher solubility. Carrageenan is categorized into three classes based on its degree of sulphation, with the Lambda type having the highest sulphation level at 40% (w/w). Lambda carrageenan does not form gels but exhibits thickening properties. Iota carrageenan is less sulphated than Lambda, enabling it to form gels when combined with calcium ions. The kappa family has the lowest possible level of sulphate ester at 20% (w/w) [94]. When exposed to potassium ions, these types of carrageenan form a robust gel and are utilized to produce transparent, cohesive films [94, 95].

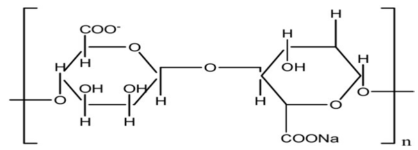
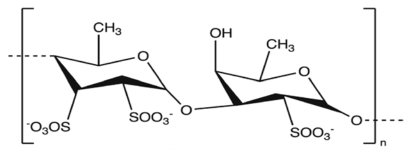
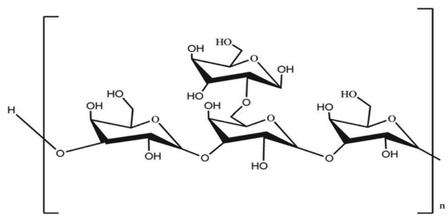
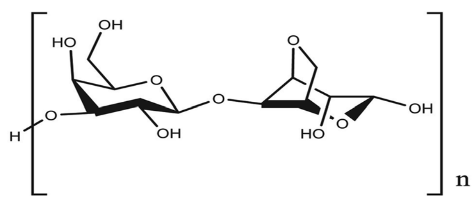
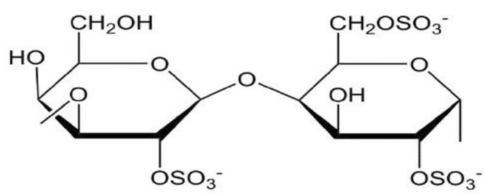
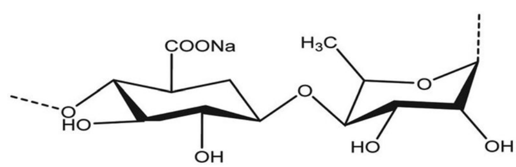
Seaweed-derived biopolymers have excellent film-forming capabilities and mechanical and barrier characteristics. Agar generates gel, due to its distinctive molecular structure. The film-forming properties of agar are influenced by factors such as concentration, temperature, and the presence of additional ingredients. Agar films are utilized in food packaging due to their non-toxic properties, a barrier against oxygen and moisture, and their capacity to preserve food quality [96, 97].

Carrageenan, a sulfated polysaccharide, used in the production of gels and films due to its exceptional mechanical properties and flexibility. The addition of carrageenan to other chemicals improves the film's tensile strength and elongation at the point of rupture, hence boosting its appropriateness for a variety of uses [98]. The molecular weight and quantity of sulfate have a major impact on the film-forming properties of carrageenan. Usually, solid films with better

Table 1 The bioactivity of the substances present in seaweeds

Bioactive compounds	Components	Benefits	References
Protein	Have different essential amino acid	Anti-inflammatory capabilities, as well as antimicrobial and antiviral activities, Communication between cells, antioxidative properties	[71]
Fat	Polyunsaturated fatty acids, ω-3-ω-6 fatty acids	Activity promoting health, antimicrobial and antibiotic capabilities, membrane flexibility, oxygen and electron transportation, adaptation to heat	[72]
Polyphenols	Isoflavones, lignans, benzoic Acid, Flavonoids, cinnamic Acid, phenolic acids, Quercetin	Anti-photoaging, anticancer activity, anti-viral, antiobesity, antioxidants, antimicrobial, host defence, antiallergic	[73]
Polysaccharide	Galactans, fucoidan, laminarin, alginates	Good Antioxidants activity, soluble dietary fiber, anti-microbial activity, antitumor and anti-inflammatory	[74]
Minerals	Entirely macro and microelements	Development and health-improving for growth and prevention of goitre disease	[75]
Sterols	Brassica sterol, desmosterol, sitosterol, uco-cholesterol	Decrease cholesterol level of blood serum in humans	[76]
Pigments	Chlorophylls and carotenoids, fucoxanthin and phycobiliproteins	Rich in antioxidants, anti-cancer, anti-angiogenic, exhibiting neuroprotective, anti-obesity, and anti-microbial properties	[77, 78]

Table 2 Chemical structures of seaweed polysaccharides

Polysaccharide	Chemical structure	References
Alginate		[81–83]
Fucoidan		[63, 84, 85]
Laminarin		[84, 86, 87]
Agar		[81, 88, 89]
Kappa-Carrageenan		[81, 90, 91]
Ulvan		[23–25]

barrier properties follow from higher molecular weight and increased sulfate. Carrageenan films show great thermal stability, which makes them quite helpful for uses requiring resistance to strong heat [99, 100].

5.2 Ulvan

Common green seaweed includes the genera Monostroma, Cladophora, Ulva, and Chaetomorpha. Ulvan is a sulfated polysaccharide, a primary cell wall component in some green seaweed species, particularly in the Ulva genus, and its applications in the agriculture, pharmaceutical, and food industries. [23–25]. Ulvan comprises α- and β-(1,4)-linked monosaccharides, including rhamnose, xylose, glucuronic acid, and iduronic acid. These monosaccharides combine to form characteristic repeating disaccharide units in Ulvan, known as aldobiuronic acid, combined with rhamnose and glucuronic acid or iduronic acid [101, 102].

The properties of Ulvan, like those of other seaweed polysaccharides, are heavily influenced by factors such as eco-physiology, the specific species it is derived from, and the methods used for extraction [61]. Ulvan gels exhibit

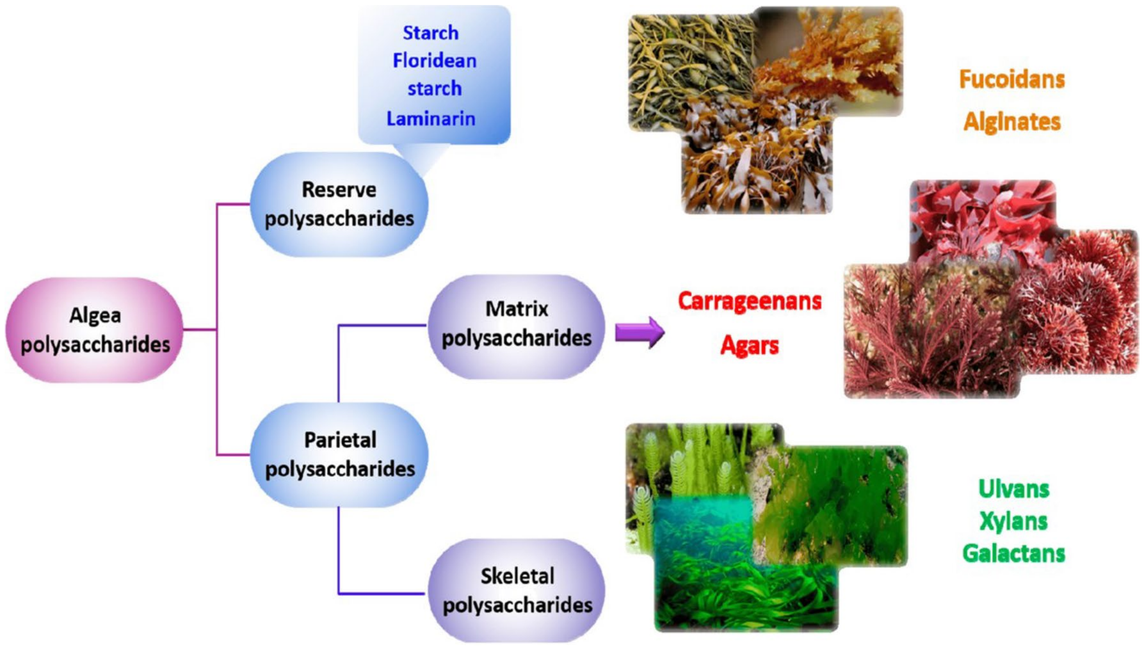


Fig. 3 The types of seaweeds and their polysaccharide compounds [92]

thermo-reversible properties, meaning they can undergo gelation and solation reversibly upon temperature changes. The conformation of Ulvan, and consequently its gel formation, is influenced by factors such as ion concentration and pH variations, with high or low ion concentrations and pH levels playing a role [103].

Furthermore, the bioactivity of Ulvan is also affected by its molecular mass, emphasizing the importance of molecular size in determining its biological effects [11]. Lower molecular weight polysaccharides have demonstrated more significant antioxidant activity and antilipidemic effect on triglycerides and HDL-cholesterol. Additionally, polysaccharides have shown inhibitory effects on various viruses, although the specific outcomes depend on the controlled dosage and the kind of virus [11, 61, 101].

Ulvan-based films for Biodegradable packaging and wound dressings are suitable with desired mechanical and barrier properties, good mechanical strength, and flexibility. Ulvan has a Sulphate group that improves its capacity for film stability by encouraging intermolecular interactions, which are fundamental for preserving film integrity under various environments [104]. Ulvan-based films prevent moisture and gas exchange and extend the shelf life of perishable goods. The study also shows that Ulvan-based films are biodegradable and environment friendly, increasing demand for sustainable packaging solutions [103]. The potential of Ulvan-based films in biomedical applications, such as wound dressings. Due to biocompatibility and its ability to form films providing a protective barrier that supports healing. Ulvan-based wound dressing enhances its suitability for wound care by reducing the risk of infection [105].

5.3 Fucoidans, alginate, and laminarin

Brown seaweed comprises many polysaccharides, including fucoidans, alginate and laminarin. These polysaccharides are essential components of brown seaweed cell walls and have various biological activities and potential applications [10]. Alginates constitute the cellular walls and intracellular matrix found in brown seaweed. They are composed of exchanging blocks of ß-D-mannuronic acid and α-L-guluronic acid [106].

Alginates possess diverse properties stemming from their unique monomer sequence. This versatility allows them to serve as a multifunctional material, finding applications as films through interaction with di and trivalent cations, as well as decaying agents in tablets by their water-swelling capabilities [106–108].

The primary polysaccharide for glucose storage in brown seaweed is known as laminarin. This compound is associated with assorted bioactivities, such as antitumor and antioxidant properties [84, 108, 109]. Its potential applications in various fields, the primary utilization of which is in the industrial sector, are specifically related to its role as a ligand. A ligand is a molecule that binds to a receptor, and in this context, it binds to pattern-recognition receptors within the innate immune system [58, 83, 110].

Fucoidan polysaccharides refer to complex sulphated polysaccharides extracted from brown seaweed. These polysaccharides consist of L-fucose and sulphate ester groups and other components such as monosaccharides, proteins, and acetyl. The characteristics and composition of Fucoidan polysaccharides vary depending on conditional factors such as season, geographical origin, extraction methods, and species. Due to their advantageous properties, Fucoidan polysaccharides are extensively utilized in biomedical applications and related fields [58, 110]. Additionally, Brown seaweed contains various other components, including terpenes, halogenated compounds, lipids, sterols, pigments, alkaloids, phenolic compounds [108, 111, 112].

6 Hydrocolloid substances in seaweeds

Seaweed produces a variety of biologically active macromolecules, including polyphenols, diterpenes, and polysaccharides, which exhibit diverse structural and physicochemical properties and serve fascinating functions. Hydrocolloids are commonly utilized due to their inherent physical properties, serving to stabilize emulsions, exhibit viscous characteristics, promote gelation, maintain suspensions and foams, and regulate crystal growth [92].

The composition of hydrocolloids in seaweeds is subject to many biological, physical, and environmental influences. These factors, including yield timing, variety differences, and extraction methods, can intensely affect the functional characteristics of the polysaccharides [113–115]. The preparation method mainly influences the viscosity, with elevated temperatures posing a particularly detrimental effect. Moreover, it is critical to maintain a pH level ranging from 6 to 7 [115]. Seaweeds offer various hydrocolloids utilized by the food and pharmaceutical sectors [116, 117].

Most hydrocolloids (agar, alginates, and carrageenan) in seaweeds are predominantly situated within the cellular structure known as the cell wall [116, 118]. Extraction of this hydrocolloid from the red algae genera (*Gelidium* and *Gracilaria*), [119], is common in Chile, India, Japan, Europe, the Philippines, and the southern United States [115, 117]. Around 25% and 17% of agar are stored in the cell walls of *Gelidium* and *Gracilaria* [115, 117]. Additional genera, such as Pterocladia, primarily encountered in (Portugal and New Zealand) and Gelidiella, found in (Egypt and India) as valuable agar resources [115, 118, 120].

The primary utilization of agar stems from its remarkable attributes in thickening and gelling. It can retain substantial quantities of soluble solids, including sugars, and elevated melting temperatures and its proficiency in preventing sugar crystallization, agar is widely desirable in the food industry, particularly for the preparation of icings and bakery glazes [81, 88].

The formation of a low gel strength matrix by agar is a distinctive property that renders it highly versatile for various applications. It finds practical utility in multiple domains, including liquid and spreadable foods and soft-textured confectionery [121, 122] Agar serves multiple functions beyond its primary applications. It can be employed as a substitute for fats, as a cryoprotectant that mitigates damage during freezing and thawing processes, and as a material for producing edible films [123–125].

Alginates, alginic acid, or algin are the most synthesized algal polysaccharides. The compounds are obtained from the cellular walls of brown algae [126, 127]. The main constituents of alginate are 1,4-β- D -mannuronic acid and α- L -guluronic acid, which comprises a linear polymer. The composition of *A. nodosum* includes 60% mannuronic acid and 40% guluronic acid [128–130].

Alginates can produce cross-linked gels that do not undertake melting, in contrast to agar. Therefore, they are utilized to produce restructured meat, vegetables, and baked products. Alginate is used independently or in combination with other hydrocolloids in the production of frozen desserts and reduced-fat products to enhance the stability of mixtures, elevate viscosity, prolong melting time, and improve organoleptic characteristics [123, 127, 129].

According to research, alginate exhibits potential as an appetite regulator and may have utility as a dietary supplement. Nevertheless, the integration of the substance mentioned above into breakfast bars does not show significant variances as a means of reducing appetite in comparison to the control group [81, 114, 124, 129]. The efficacy of alginate as a coating film in cooked chicken nuggets was observed, resulting in enhanced heat distribution and reduced cooking duration [82, 131, 132].

Applying sodium alginate as a coating agent on bream yielded promising outcomes, including enhanced antioxidant capacity. This attribute is believed to inhibit fish spoilage and prolong its shelf-life effectively [133]. Alginate is a coating agent that enhances sensory characteristics and decreases water loss in food products. It has antimicrobial agents and anti-browning agents, such as ascorbic acid and citric acid, to maintain the colour of freshly cut Kent mangoes and enhance their antioxidant capability [74, 115, 127, 134].

The carrageenans are characterized by the number and position of sulphate groups on the repeating galactose units. Carrageenan's capacity to establish linkages with milk proteins, yet when present in low concentrations of 0.01%, represents a highly advantageous characteristic [135–137].

Carrageenans and semi-refined carrageenans are utilized in the food industry because they gel, emulsify, thicken, and stabilize. Carrageenans are frequently utilized as a constituent in dairy commodities, particularly in frozen desserts like ice cream [58, 81, 90] and milk-based products [74, 115]. According to the findings of some other studies, the shelf life of fresh chicken breasts increased by utilizing carrageenan as an encompass film or in bakery products like bread [138]. Table 3**.** shows some physicochemical and functional properties and applications in different industries and food and beverage products [139]

7 Properties of seaweed-based films

Seaweed is commonly utilized in packing, culinary, and biomedical applications because they have biocompatibility, absorbability, and biodegradability. Hydrocolloid polysaccharides are derived from seaweeds and utilized as biopolymeric films [149]. These compounds have antimicrobial properties that prevent food packaging from microbial spoilage. Seaweed films are flexible and can be modified by merging with adding additives and other biopolymers. This flexibility allows the film's modification for specific needs like strength, permeability, and moisture resistance. Overall, seaweed films provide an eco-friendly alternative to traditional packaging materials [150, 151]. Their biodegradability, flexibility, and versatility make them a favorable solution for businesses seeking to reduce plastic waste and moderate its harmful impact on the environment [152].

The toxicity of chemicals in food packaging can be relieved by using natural compounds like seaweed, which contains organic compounds. Seaweed, with its high organic content, can be an effective active agent or raw material. When combined with biodegradable polymers, these materials offer enhanced sustainability, functionality, and sensory properties. Seaweeds produced environmentally friendly and biodegradable packaging materials, as shown in Fig. 4 [74].

Seaweed-based films have biodegradability, and distinct visual characteristics, particularly transparency are essential for applications in food packaging and coating. Agar and carrageenan are derived films due to their gel strength, low turbidity, high transparency and good appearance [153, 154]. The molecular structure of these polysaccharides allows for the formation of films with minimal light scattering, enhancing transparency. Casting and extrusion techniques can influence the film's microstructure, affecting its optical clarity the film's thickness and uniformity, which are crucial for achieving high transparency [155, 156].

During film formation, drying conditions such as temperature and humidity, can impact the film's surface smoothness and transparency [157]. Additives and plasticizers are incorporated into seaweed-based films to enhance their mechanical properties and flexibility and affect appearance [158]. A smooth surface is essential for achieving high transparency and is achieved through control of the film-forming process and appropriate additives [159]. The colour of the film can be modified by specific seaweed or natural pigments, which can enhance the visual of the packaging material and maintain transparency [160].

7.1 Mechanical properties

At present, diverse potential implementations exist for packaging that incorporates seaweed and other composite materials [161]. Comprising chitosan and κ-carrageenan (κ-CG) determined the mechanical and structural properties of the blend film. The results indicate that integrating kappa-carrageenan into the chitosan film improved its flexibility and achieved a uniform and smooth surface. Furthermore, it was found that incorporating κ-CG reduced water solubility and extension at break. So increased moisture affinity, enhanced tensile strength, and improved hydrophobicity [162] Another investigation was of a film composed of kappa-carrageenan and chitosan combined with allyl isothiocyanate. The polysaccharide film with opposite charges displayed favorable coating characteristics and improved gas barrier performance. Moreover, it delayed the release of bioactive substances incorporated into the film. The Chitosan/ kappa-carrageenan complex film demonstrated enhanced antimicrobial effectiveness against *Bacillus subtilis* and *Bacillus cereus,* as supported by the results [74]

A nanocomposite film was formed using polylactic acid and laminated agar/ kappa-carrageenan /clay bio-nanocomposite. The film showed improved properties, such as increased tensile strength, water vapour permeability, water uptake ratio, water solubility, and enhanced thermal stability. kappa-carrageenan and polydextrose matrix plays an essential

Table 3 Functional properties of hydrocolloids and their applications

Seaweeds hydrocolloids	Functional and Physicochemical properties	industries	Food & beverages	References
Carrageenan	Thermo-reversible, good gelling (Gell Strength: 100–350 g/cm2, Gelling Point: 30–50 °C, Melting Point: 50–70 °C, Appearance: yellowish powder) thickening (Viscosity: 30–300 cP) stabilizing, emulsifying, and water holding properties	Thickenings for toothpaste, eye drops, beads for the controlled released system, cosmetics, suspending agents in antacids, lotion and creams, suppositories, Cosmetic things, and the paint industry	Puddings, milkshakes, canned food, ice cream, desserts, vegan alternatives to gelatine, processed meat, cream thickener, chocolate milk, fruit juices, beer, jam, pet food, sauces, and gravies,	[139–142]
Alginate	Fast absorption of water (Soluble in water and insoluble in ethanol and ether), Excellent gelling, stabilizing, thickening agent (viscosity is high and Appearance is yellowish powder), Thermo-irreversible (with the presence of calcium, Ca2 +), melting point is > 300 °C	Dental impression, filling agents, matrices to drug delivery systems, additives in dehydrated products, wound dressing, paper and textile industry, medicine for rheumatoid arthritis, emulsifiers for paint and plastic industry, antacids, prosthetic devices, Heavy metal absorption and purifier for wastewater, material for artificial fiber, biodegradable sutures, lubricant, refining	Thickeners in drinks, cold prepared bakery cream, pie and pastry filling, ice cream, jelly, restructured foods, dessert gels, instant pudding,	[139, 141, 142]
Agar	Thermo-reversible, Excellent gelling agent (gelling point: 32–45 °C, melting point: 85–95 °C, viscosity: 10–100 cP, Appearance: yellowish powder), high temperature resistant	Thickeners for toothpaste, beads for the controlled released system, Inhibitor of Papilloma, suppositories, Cosmetic and paint industry, dengue and herpes virus, cosmetics, lotion, and cream, suspending agents in antacids, and eye drops	Puddings, milkshakes, desserts, cream thickener, chocolate milk, vegan alternatives to gelatines, tofu, ice cream, processed meat, canned food, beer, sauces and gravies, fruit juices, jam, pet foods	[141–144]
Ulvan	Structural, complexity, and bioactivity viscosity is 10–100 cp, slightly granular, appearance: powder is pale yellow to light green	Used in cosmetics, biomaterials, fibres, scaffolds, pharmaceutical gels, fuel, antibacterial, and drug delivery systems	Food packaging, food preservation, beverages, juices, healthy drinks, food and feed products	[145–148]

Fig. 4 Different types of Seaweed and in their applications in food packaging [74]

role in the stability and quality control, enabling the diffusional mobility of α-lionic acid. An electrostatic attraction was observed among the components of the polylysine, kappa-carrageenan, and pectin film, forming a robust complex that acts as an effective antimicrobial delivery system [151, 163].

A study investigated the reinforcement of nanocrystalline cellulose in alginate-based biodegradable nanocomposites. The findings exhibited improvements in tension strength, modulus of elasticity, thermal stability, and structural and physical characteristics of the barrier [164]. They also reported decreased swelling properties, water vapour permeability, and extension at the discontinuity of the nanocomposites [164]. The researcher prepared biopolymer films using thymol-loaded nanostructured lipid carriers and nanoemulsions added to Ca-alginate solutions. It increased the films' porosity, surface roughness, thickness, and water vapour permeability and decreased the films' water contact angle, mechanical strength, and swelling ratio [165].

A study found that agar and nanocrystalline cellulose decreased water solubility, water vapour permeability, tensile strength, and elastic modulus. This unique packaging technique improved food safety, shelf life, water contact angle, swelling ratio, viscosity, and elongation at break [89]. Table 4 shows the Modern Application of seaweed polysaccharides in (edible film, coating, and active) packaging systems.

7.2 Antimicrobial properties

Active packaging relies heavily on antimicrobial packaging as it plays a crucial role in addressing the prominent food safety issue within the food industry [74]. When aiming for sustainable and secure packaging, it is essential to consider the inclusion of natural antimicrobial substances like chitosan [182]. Through agar diffusion tests, multiple research studies have demonstrated the antimicrobial activity of crude seaweed extracts that contain a combination of polysaccharides in a survey conducted by [183].

The biochemical characteristics and polysaccharide composition of brown seaweed *Chaetomorpha antennina* were assessed by extracting its polysaccharides using both traditional and alternative methods. Mixed fucoidans extracted using microwave and subcritical water techniques prevented *Escherichia coli* growth. Enzyme-ultrasound, ultrasound microwave, and subcritical water extraction techniques showed antibacterial activity against *Staphylococcus aureus*. All fucoidans had an antiviral impact on HSV-2 infections, regardless of extraction method [184].

Multiple studies have demonstrated that dietary seaweed preparations have a therapeutic effect on infectious diseases in fish [185]. The therapeutic effect of orally administered seaweed polysaccharide preparation, such as *Ascophyllum nodosum*, is a bacterial infection model involving mammals. Previous studies have explored the incorporation of pure

Table 4 Recent Application of Seaweed Organic Compounds in (edible film, coating and active) Packaging System

Compounds	Packaging Matrix	Properties of materials	References
Carrageenan	Chitosan	Preserve the longan fruit while minimizing alterations in quality and quantity, resulting in reduced water loss, weight loss, and respiratory rate in coated fruits	[166]
Fucus vesiculosus	Whey protein	It effectively prevents lipid oxidation in packaged poultry meat, maintaining this protection for at least 25 days during storage while fortifying the thickness, tensile strength, and elastic modulus	[167]
Sodium Alginate	Carboxymethyl cellulose, CaCl2, Pyrogallic acid	It demonstrates efficacy against *E. coli* and *S. aureus*, increasing moisture content, water vapour permeability, oxygen permeability, and excellent elongation at break	[168]
Sodium Alginate	Lemongrass oil	The films successfully suppressed the proliferation of *E. coli* and *L. monocytogenes* bacteria and achieved a controlled release of lemongrass oil through microencapsulation	[169]
Furcellaran	Gelatin hydrolysate/Rosemary extract	They included heightened antioxidant activity, elevated thickness, increased water content, enhanced tensile strength, and variations in color at different pH levels	[170]
K and I carrageenan, and Alginate	Glycerol	Alginate contributes to film uniformity and transparency. I-carrageenan influences the film's opacity, while k-carrageenan enhances moisture resistance and tensile properties	[171]
Sodium Alginate	Sodium carboxymethylcellulose, collagen, and Lactococcus lactis	It successfully hinders the growth of *S. aureus* over seven days, but when *Lactococcus lactis* is added, it decreases gloss and transparency	[172]
Alginate	Pullulan and Capsaicin	They demonstrate vigorous antibacterial activity against *E. coli and S. aureus and* improve tensile strength, water vapor permeability, and surface contact angle	[173]
Sodium Alginate	Gelatin-tea polyphenols	Raising the levels of tea polyphenols leads to enhanced antioxidant properties and physical characteristics. However, this also results in compact extension at break and decreased water vapor permeability. On the positive side, it boosts tensile strength, contact angle, and cross-linking	[174]
Sodium Alginate	Ferulic acid	There was no observed inhibition zone against Klebsiella pneumonia and Salmonella enterica. However, an increase in the concentration of ferulic acid resulted in heightened antioxidant activity	[175]
Agar	Nano-bacterial cellulose	Including bacterial cellulose, which reduces moisture content, water solubility, and water vapour permeability while increasing tensile strength from 22.10 to 44.51 MPa. Additionally, it led to improved crystallinity and enhanced thermal stability	[176]
Agar	Starch and Maltodextrin	Enhanced film-forming capability and hydrophobic characteristics are achieved. Including maltodextrin leads to the formation of highly compatible and flexible starch-agar films. Furthermore, solubility increases with higher maltodextrin concentration	[177]

Table 4 (continued)

Compounds	Packaging Matrix	Properties of materials	References
Semi-refined carrageenan and Ulvan	Glycerol	Semi-refined carrageenan and Ulvan films exhibit a notable capacity for chelating metal ions. Ulvan polysaccharide-based films display robust hydroxyl radical scavenging activity. Films with lower molecular weights demonstrate superior antioxidant activity	[178]
Sodium Alginate	Pomegranate peel extract, Chitosan	Effectively maintained the nutritional properties, delayed senescence, and enhanced the visual characteristics of guava	[179]
Sodium Alginate	Oregano essential oil (1.5–2.5% w/w), mandarin fiber (0.5% w/w)	Efficiently removes pathogens like Staphylococcus aureus and prolongs the shelf life of low-fat sliced cheese	[180]
κ-carrageenan	Chitosan	There is a decrease in weight loss and a positive impact on reducing disease infection in dragon fruit stored at 10 °C and 90–95% relative humidity. Additionally, the freshness and bract chlorophyll content are maintained for 30 days	[181]

saccharides like carrageenan and alginate into polymer films; however, these films have demonstrated limited and no detrimental impact against *Escherichia coli* and *Listeria monocytogenes* [186]

However, a film production including the extracts derived from seaweed was developed, and the findings demonstrated a remarkable area of inhibition against gram-positive bacteria. This finding illustrates that the extract can sustain its antibacterial activity. Research on crude seaweed extract shows significant potential for antimicrobial properties of algae polysaccharides [86]. Studies on polysaccharide films have shown their versatility in incorporating different materials, including polymers, nanoclays, and copper nanoparticles. This adaptability enables the production of active antimicrobial packaging that might inhibit microbe growth, thereby increasing the safety and durability of packed products [74, 187, 188].

To investigate the development of films using alginate-extracted seaweed biomass. In their research, control films made of durian starch and carrageenan did not exhibit any inhibitory effect on *Staphylococcus aureus*, as observed in the disk diffusion assay. However, upon incorporating ten weight percent (wt%) carvacrol into the film and subjecting it to rediffusion for 24 and 48 h, a notable and comprehensive suppression of the growth of gram-positive bacteria was observed [132].

Similarly, the composite film based solely on pure carrageenan did not demonstrate antibacterial effects against *E. coli* or *Listeria monocytogenes*. This lack of antibacterial activity persisted even after incorporating nano-clay or nano-silver into the film [138]. An agar blend was studied for its antimicrobial properties against food-borne pathogenic bacteria. Initially, the blend presented no significant antimicrobial activity against gram-positive and harmful bacteria. However, the combination acquired antimicrobial properties upon adding seaweed nanoparticles, which possessed robust antimicrobial activity [188, 189]. A study of the antimicrobial activity of an aqueous extract of *Kappaphycus alvarezii* found that the raw extract was effective against gram-positive bacteria, like *Staphylococcus aureus* and *Bacillus cereus*. The inhibition of *Staphylococcus aureus* was more significant than that of *Bacillus cereus* [190].

7.3 Antioxidant properties

Lipid oxidation significantly influences the quality of food and food products. The formation of agents, including free radicals, during oxidation, can have cytotoxic properties, mutagenic and carcinogenic, leading to serious health issues. Furthermore, oxidation negatively impacts food's shelf life and nutritional value, decreasing product quality [191]. Antioxidant packaging prevents the degradation of lipids and proteins in packaged food and products. Active packaging effectively counteracts oxidation by incorporating or coating antioxidants onto the packaging film. Natural antioxidants have recently gained popularity due to a desire to reduce synthetic ingredients in packaging. Biological additives are considered safe to consume and provide additional health benefits, making them appealing to the market [132, 189, 191].

Gracilaria lemaneiformis exhibited less antioxidant activity due to its non-sulfated polysaccharide nature. On the other hand, green seaweed polysaccharides demonstrated high antioxidant activity, and brown seaweed polysaccharides also displayed a more reducing power [192]. The antioxidant effects were higher than those observed in methanolic or ethanolic seaweed extracts. Incorporating the extract into a Polly vinyl Alcohol film showed a substantial enhancement in radical scavenging activity, surpassing the effects of pure Polly vinyl Alcohol films and those with seaweed extracts [193–195].

More studies have revealed Lambda-carrageenan to have significant antioxidant activity. They provided evidence that incorporating antioxidant-rich polysaccharides can effectively prevent the oxidative deterioration of food [193]. A DPPH experiment assessed the antioxidant capacity of a carrageenan and mulberry extract film. The results showed that carrageenan had an antioxidant activity that depended on the quantity employed and that mulberry extract further increased this activity [193]. The DPPH assay revealed that the pure κ-carrageenan film exhibited moderate antioxidant activity due to its inherent natural polyphenols, nevertheless, including plant essential oils enhanced these results [196].

The results suggest that polysaccharides exhibit varying antioxidant activity, rendering them appropriate for deployment in antioxidant packaging. However, the incorporation of constituents such as essential oils derived from plants and extracts of mulberry can be utilized to amplify the antioxidant characteristics, thereby ensuring efficient mitigation of lipid oxidation and augmenting food safety. Additionally, additional investigation is necessary to comprehensively understand the antioxidant properties exhibited by diverse seaweed polysaccharides and extracts. This will maximize seaweed's antioxidant properties in active food packaging [138].

The use of active components in antioxidant and antimicrobial packaging films to achieve the desired effects on the product. It further emphasizes the need to determine the feasibility of producing such films by examining the active agent diffusivity and release rate into the food [197]. The release of the component is crucial, as it should neither be extremely rapid, which could cause migration about the internal part of the food, nor excessively slow, which would delay attaining the required inhibitory concentration [12].

A study investigated the migration of natamycin from an antimicrobial film made of an alginate/pectin blend. The researchers measured natamycin concentration in water and determined parameters related to its release. Results showed that natamycin release in pure pectin film occurred within 30 h, composite film over 70 h, and pure alginate film over 800 h. Adding alginate reduced the natamycin diffusion rate, suggesting higher compatibility between natamycin and alginate than pectin [198].

A study analyzed the movement of sorbic acid from a film made of polylactic acid and focus. The release of sorbic acid was slower in 95 wt% ethanol at 40 °C compared to pure polylactic acid film. However, the pure polylactic acid film's release was significantly lower in 10 wt% ethanol. The polylactic acid/fucus blend showed slightly higher diffusion coefficients, possibly due to weaker immobilization of the antimicrobial agent [199].

The study examined calcium release from alginate films when exposed to ethanol, acetic acid, and oleic acid. It found that the concentration of nanoparticles significantly impacted the release rate, with lower concentrations resulting in slower release due to stronger interactions. Conversely, higher nanoparticle concentrations led to particle aggregation, reducing chemical interaction and accelerating release. Moreover, the acidic nature of acetic acid hastened release compared to ethanol. In contrast, the solubility of nanoparticles in oleic acid and the insolubility of the alginate layer further increased release rates in oleic acid [132].

8 Application of seaweed based food packaging

8.1 Fresh produce packaging

Seaweed-based films have great potential for preserving freshness in products. These films create a protective barrier that prevents the exchange of gases and moisture between the packaged produce and its conditions. Altering the atmosphere of fresh fruit packaging effectively slows down the process of deterioration [74].

Moreover, seaweed-based coatings offer barrier properties that minimize water loss from the product, thereby reducing shrinkage and protecting its firmness. This preservation effect significantly prolongs the freshness and appeal of perishable fruits and vegetables over an extended period. Additionally, these films prevent moisture loss, thereby retaining the inherent juiciness of the produce and improving its sensory characteristics [200]. Packaging fresh produces a critical challenge, preserving the desired texture and nutritional post-packaging values. Seaweed-based films present an ideal solution to attempt these challenges effectively. Their formulation advances a microenvironment favourable to maintaining the texture, thereby modifying issues such as browning, wilting, and softening [201].

Seaweed-based films are crucial in preserving the nutritional value of fruits and vegetables by shielding them from light and preventing the degradation of vitamins and antioxidants. These films also contain bioactive components that can be transferred to vegetables, providing additional health benefits. They extend shelf life and maintain texture and nutritional quality by creating a modified environment that reduces respiration rate and moisture loss, enhancing the freshness, appearance, and nutritional value of packed produce, reducing food waste, and increasing customer satisfaction [200].

Figure 5 A study on tomatoes coated with seaweed found that the seaweed extract, specifically *Kappaphycus alvarezii*, had superior antibacterial and antifungal properties compared to *Sargassum tenerrimum*. The study also assessed quality parameters and shelf life, finding that *K. alvarezii* was more effective in preserving tomato fruit quality and enhancing it during storage. The findings suggest that seaweed gel can improve tomato quality and extend shelf life [134].

8.2 Meat and seafood packaging

Using seaweed-based films is advantageous in protecting and upholding the property of meat and seafood products. Acting as protecting barriers, these coatings effectively block the oxygen and moisture, which contribute significantly to the degradation of seafood and meat. Modified atmosphere packaging and seaweed-based films increase the shelf life of products by inhibiting bacterial growth that leads to spoilage and minimizing oxidative reactions, thus preventing the deterioration of the items [151].

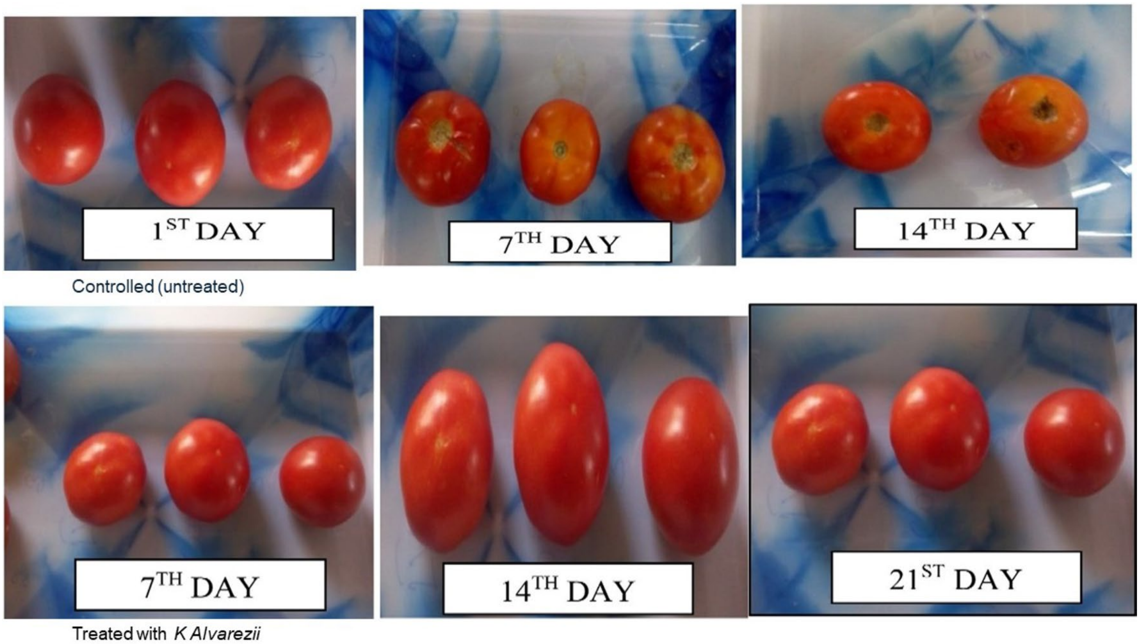


Fig. 5 Shows the effect of texture of seaweed-coated and uncoated tomatoes during storage [134]

These films also possess antibacterial properties due to bioactive compounds found in seaweed, inhibiting harmful bacteria growth, decreasing foodborne disorders, and improving the safety of packaged meat and seafood [202]. Seaweed films have barrier properties that reduce the loss of natural fluids and flavors and preserve the quality of packaged meat and seafood [203].

Seaweed-based films provide barrier properties to maintain the freshness and reliability of packaged items by minimizing humidity loss and resistance against external contamination. They prevent dehydration in meat, ensuring tenderness and juiciness. They retard bacterial growth and microbiological spoilage, extending product shelf life [204].

Seaweed-based films maintain quality and extend shelf life in the highly perishable seafood sector and help to retard deterioration. Preserving seafood in this way enhances the taste, texture, and colour of packaged seafood, reducing the likelihood of food waste [74]. Industries use this packaging for meat and seafood to extend shelf life, reduce food waste, and improve product quality and safety. This sustainable and environmentally friendly method prolongs the freshness of these products, ensuring optimal consumer experience [203]

Figure 6 Shows that the study investigated the impacts of edible coatings made from agar/sodium alginate (AS) and AS combined with ginger essential oil on refrigerated fresh beef quality and shelf life. Results showed that AS + GEO beef maintained enhanced sensory characteristics during storage, proposing potential for further development of antibacterial coating material for preserving frozen beef [205].

8.3 Bakery and confectionary packaging

Seaweed-derived films are used in packaging confectionery to maintain texture and freshness. They act as protective barriers, preventing gas and moisture exchange between products and their environment. This helps keep the desired texture of baked goods by minimizing absorption and reducing product moisture loss, preventing staleness, hardness, or dryness. [200]. Seaweed-based films help preserve baked goods' freshness by creating a microenvironment within the packaging, slowing the staling process, and preventing moisture movement between crust and crumb components, thus keeping their distinct textures and flavours during ageing [203].

These films are essential for preventing staleness and preserving shelf durability in baked goods and confectioneries. They provide a shield against moisture absorption, preventing texture and flavour changes. This helps maintain the crunchiness, fluffiness, and freshness of baked goods like cookies, pastries, and bread [161]. These films preserve

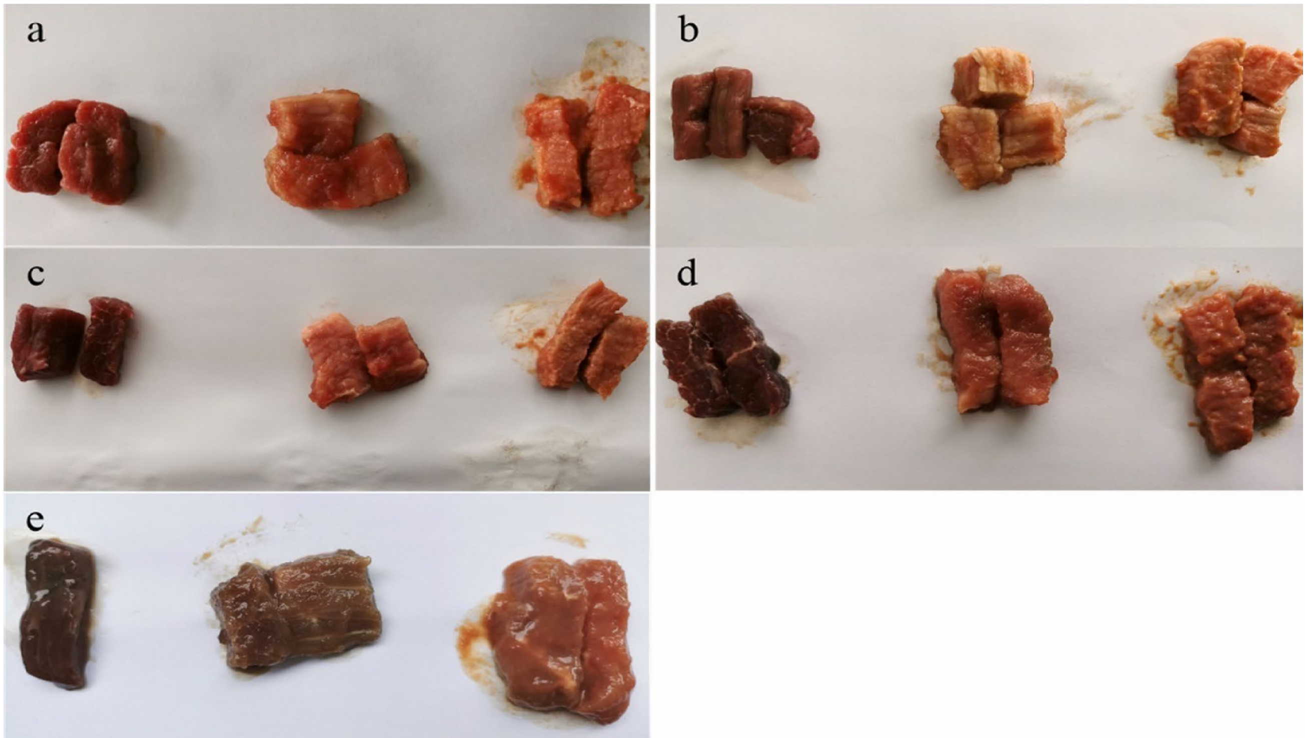


Fig. 6 Images show meat samples texture for different storage times: **a** 3: **b** 6: **c** 9: **d** 15 and **e** 24 days, stored at 4 °C [205]

the shelf-life stability of bread and are sweetened by shielding them from outer effects that accelerate spoilage. Acting as a barrier, these films block light, which can degrade light-sensitive elements such as flavours and colors, etc. Lowering light exposure helps maintain packaged foods' visual appeal, taste, and aroma [206].

9 Conclusions and different challenges

Seaweed contributes essential nutrients, textures, and health-promoting components to food products. Seaweed-based films prefer sustainable food packaging, renewable sourcing, biodegradability, and consumer acceptance. Innovations in seaweed-based films have the potential for sustainable and environmentally friendly packaging solutions, contributing to a more sustainable and circular economy. Seaweed's essential nutrients contribute to gelling agents, colourants, and other food products. Seaweed's biodegradability, transparency, antioxidant, and antimicrobial properties determine its potential in sustainable food packaging. Combining seaweed with biopolymers and additives enhances packaging attributes, yet further research is needed for optimal performance. Incorporating seaweed into polymers aligns with sustainability goals and requires examination of specific effects. Ensuring safety and tailoring mechanical properties through polymer blends or natural additives shows promise for eco-friendly packaging.

Enhancing mechanical strength and durability is crucial for ensuring suitability for packaging and transportation. Research is needed to improve stability and usability over extended periods by mitigating degradation factors like moisture absorption and oxidation. Developing effective and eco-friendly mass production and handling methods is essential for increasing demands. We focus on researching competent and cost-effective techniques to enhance economic competitiveness in production and processing. Furthermore, we are exploring composite materials and novel formulations to enhance functional properties. Detailed studies on seaweed strength, antibacterial properties, and controlled release are needed. Regulatory standards and addressing production costs are crucial for commercial viability. Adapting seaweed-based films for various applications through polymer blends is significant for eco-friendly packaging.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The authors declare no competing interests.

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