Food packaging based on biodegradable polymers from seaweeds : a systematic review

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Abstract. As a result of its brief lifespan, food packaging contributes significantly to environmental contamination through the rapid accumulation of plastic in the environment. In order to mitigate these impacts and provide a food packaging solution that is more environmentally sustainable, researchers have created biodegradable and biobased polymers, which are presently being introduced to the market. The current state of research regarding the incorporation of seaweed into food packaging and active packaging is summarized in this study. In order to emphasize the benefits of polysaccharides and draw attention to the constraints of current research, this study also presents a synopsis of the effects of seaweed incorporation on a range of properties, including chemical, physical, thermal, antioxidant, antimicrobial, and mechanical attributes, in addition to the release of active compounds. A multitude of polysaccharides, including those found in seaweed, have the potential to enhance the antibacterial, thermal, and mechanical properties of these polymers, among other attributes. In addition to increasing hydrophilicity and mechanical properties such as tensile strength and elongation at break, they suggest employing it as active packaging. This is feasible as a result of the antioxidant properties of seaweed, which inhibit lipid oxidation and decrease toxic, mutagenic, or carcinogenic free radicals, thereby extending the nutritional value and shelf life of food. Certain varieties of seaweed have exhibited the capacity to impede the proliferation of bacteria classified as gram-positive and gram-negative. Thus, their prospective application as antimicrobial packaging is indicated.

1 Introduction

A crucial component of the contemporary food sector is packaging. Food preservation is essential as it guarantees both the food's safety and integrity [1]. Due to these benefits, packaging is a crucial component of our supply chain; yet, there are drawbacks as well, including the possibility of contaminant residue transfer, issues with cost and energy efficiency, and sustainability [2]. For food packaging, materials like glass, paper, different metals, and plastic are regularly used; however, plastic is the material that is used most frequently [3]. The majority of plastic used in food packaging is thermoplastic plastic, which softens when heated and subsequently cools to its original state [4].

The most widely used thermoplastics are polypropylene, polyethylene terephthalate, low-density polyethylene, and high-density polyethylene [5,6]. These materials typically have a

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lifespan of less than a year before being thrown away. Because of its brief lifespan, plastic garbage in the environment accumulates quickly. Every year, currents and wind carry 10–20 million tons of plastic into the ocean, harming the marine environment's ecosystem and fauna in the process. Additionally, it causes microplastic to enter the food chain and include hazardous compounds [7]. Significant progress has been achieved in the search for workable, environmentally acceptable alternatives, such as biodegradable and/or biobased polymers, through a number of research conducted in recent years [8,9].

Natural and fossil fuels are used to create biodegradable polymers like polylactic acid (PLA) and polyhydroxy butyrate (PHB), among others [10]. In a brief amount of time, the microbes may metabolize these biodegradable polymers and then restore them to nature. In contrast, bio-based plastics are entirely composed of bio-based materials such as proteins, polysaccharides, and microbial polyesters that are either created by microorganisms through fermentation or taken from plants or marine organisms [11]. The polysaccharides employed in bio-based polymers are both non-toxic and capable of undergoing biodegradation. These biological materials are also recognized for their biocompatibility, which refers to their ability to function appropriately within a specific application while eliciting an appropriate response from the host. Therefore, these characteristics offer numerous advantages for food packaging, particularly for use in edible coatings and films. Polysaccharides provide a sustainable option for active packaging because of their inherent biological characteristics, such as antibacterial and antioxidant properties [12]. Seaweeds, which are rich in polysaccharides, have great potential as a raw material for active packaging. When combined with biodegradable polymers, they offer a more environmentally friendly alternative to traditional materials [13].

2 Materials and Methods

In this study, we collected the references (papers) from Indonesia in Google Scholar. Recent references published between 2019 until 2023 were retrieved using some keywords "Food Packaging Seaweeds" and "Food Packaging polymers". The present review offers a comprehensive synthesis of the existing research concerning active packaging and the application of seaweed in the realm of food packaging. Moreover, it provides an exhaustive examination of the ramifications that arise from the incorporation of seaweed into packaging materials, with a particular focus on the implications for the materials' chemical, mechanical, physical, thermal, antioxidant, and antibacterial properties. This article presents a succinct summary of the active compounds that are liberated when seaweed polysaccharides are integrated into food packaging. Furthermore, prospective trends and legal considerations concerning the use of seaweed polysaccharides in food packaging were also addressed in the conversation.
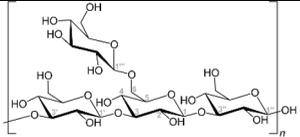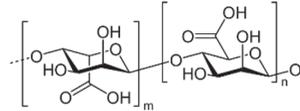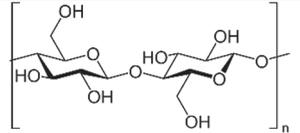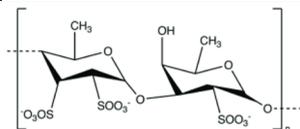
3 Results and Discussion

3.1 Seaweeds

Benthic algae, or seaweeds, are multicellular, large algae that grow faster than land plants. Because seaweeds have higher photosynthetic efficiencies than terrestrial plants, they acquire biomass faster [14]. It contributes significantly to the aquatic biomass, generates almost half of the primary productivity on Earth, and is widely utilized for feed and other purposes. Seaweed is quite abundant, thus during the past ten years, as demand for it has grown, seaweed agriculture has flourished. Consequently, a substantial quantity of seaweed waste is generated from diverse industrial procedures, including the food industry, which imposes strict quality standards on the seaweed [15]. Within a circular economy, these waste materials can be utilized as a third-generation biomass for various purposes such as pharmaceuticals,

animal feed, agriculture, and biofuels. Due to the potential severe impact on the marine ecology, it is crucial to recycle the waste material instead of releasing it into the environment. It also implies that algae have a great deal of potential for use as a sustainable energy source and as high-value products [16].

Around the world, seaweed has over 10,000 different species and can grow up to 180 meters below the surface on solid surfaces like granite. It is a highly significant marine resource in terms of its rich biodiversity. Seaweeds can be classified into three classes according to their pigmentation: red (Rhodophyta), brown (Ochrophyta), and green (Chlorophyta). The seaweeds contain a diverse range of bioactive compounds that have multiple applications in the fields of medicine, agriculture, and pharmaceuticals. The several varieties of seaweeds are listed in Table 1, along with corresponding polysaccharides and their molecular structures [17,18].

Table 1. Significant seaweed polysaccharides and their chemical composition.

Seaweed	Polysaccharide	Chemical structure	Sugars	Ref
Brown seaweed	Laminarin		Glucose, guluronate, sulphated fucose, mannuronate, mannitol	[14-16]
	Alginates			
	Cellulose			
	Fucoidan			
Red seaweed	Agaropectin		3,6-anhydro-D-galactose, glucose D-galactose, D-fructose,	[17-20]
	Carrageenan			
	Cellulose			
	Xylans			
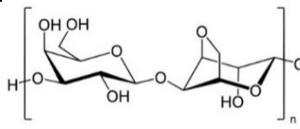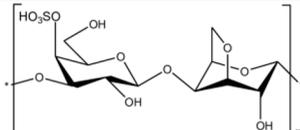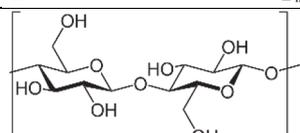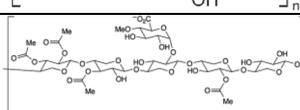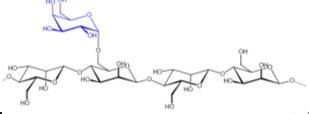
	Mannans			
Green seaweed	Ulvan		Rhamnose, galactose, Glucose, xylose, uronic acids,	[21-22]
	Starch			
	Xylopyranose			
	Glucopyranose			
	Xyloglucan			
	Glucuronan			
	Cellulose			
	Hemicellulose			
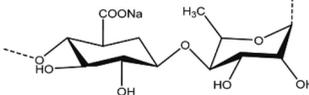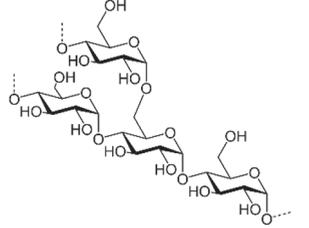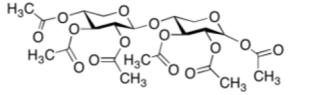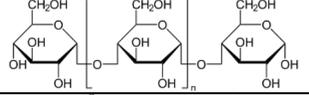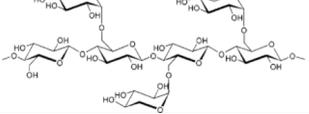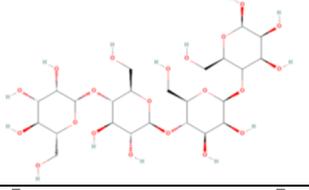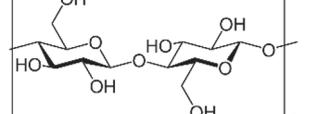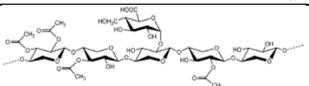
The red and blue pigments phytocyanin, phycoerythrin, and chlorophyll A differentiate red seaweeds from their brown and green counterparts. Red seaweed is home to a vast array of species due to its varied life cycles and plant morphologies. The species that occur most frequently include Poryphyra capensis, Aeodes orbitosa, and Notogenia stiriata [23]. These seaweeds contain sulphated galactans, which are extensively utilized biopolymers in the food industry, specifically for products like agar and carrageenan. Agar and carrageen are categorized as non-digestible oligosaccharides with immune-modulating, prebiotic, anti-tumor, and antioxidant properties [24]. They are also non-cariogenic in humans. Agarose and agaropectin, the two primary ingredients of agar, have structural and functional similarities to carrageenan. Due to its gelling, emulsifying, and thickening qualities, it can be used commercially in food, medicine, and other uses in addition to being beneficial in science.

Agar's chemical structure is made up of residues of α(1–4)-3,6-anhydro-l-galactose and β 9(1–3)-d-galactose, with tiny amounts of esterified sulphate up to 6% (w/w).

Carrageenans are composed of α (1–4)–3, 6-anhydro-d-galactose and β (1–3)–d-galactose backbones that are sulphated to differing degrees [25]. It is hydrophilic and anionic, and the degree of sulphate ester determines how soluble it is—the more sulphate ester, the more soluble it is. They are separated into three classes based on the degree of sulphation; the Lambda type has the maximum sulphation at 40% (w/w). They have thickening qualities but are unable to form gels like the other carrageenans. Because iota carrageenans have less sulfur than lambda carrageenans, they may gel softly when calcium ions are present. The Kappa family of carrageenans has the lowest sulphate ester content, with a sulphate level of 20% (w/w). The carrageenans are employed to produce cohesive and transparent films due to their ability to form robust gels when exposed to potassium ions [26].
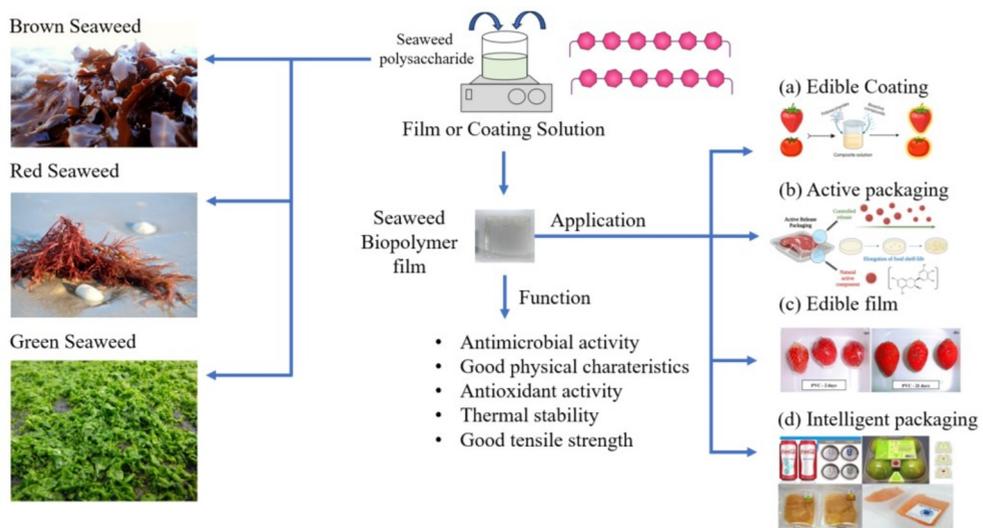
Fig. 1. The process of creating food contact materials using seaweed. (a) The impact of edible coatings on the longevity of fresh strawberries has been studied [29]. (b) Active packaging that is biodegradable and has controlled properties [30] (c) The application of edible coatings on fruits and vegetables [31] (d) Several instances of intelligent bio-based food packaging are provided [32].

Green algae inhabit both saline and freshwater due to the presence of chlorophyll a and b, the pigments responsible for their green hue. Common green seaweeds consist of the Chaetomorpha and Cladophora species, in addition to sea lettuce, which is composed of the Ulva and Monostroma species. Ulvan, which makes up an estimated 36% of the dried weight of green seaweed, is a complex carbohydrate found in its cell walls [27]. There are a multitude of prospective applications for this substance in the domains of agriculture, medicine, and sustenance. The substance's structure is determined by the presence of monosaccharides that are interconnected via α- and β-(1,4) bonds. Among these monosaccharides are rhamnose, glucuronic acid, xylose, and iduronic acid. Additionally, the substance comprises repeating disaccharide units, aldobiuronic acid and ulvanbioses. Similar to various other seaweed polysaccharides, the properties of ulvan are substantially influenced by its eco-physiology, source species, and extraction methods. Recent research has shown that ulvan gels exhibit thermo-reversibility, meaning they can be reversed by changes in temperature. Additionally, variations in pH and ion concentration can affect both the structure of ulvan and the formation of the gel. The bioactivity of ulvan is influenced by its molecular mass. Fractions with higher molecular weight exhibit a more pronounced ability to reduce total serum and LDL-

cholesterol levels, whereas polysaccharides with smaller molecular weight demonstrate a greater antioxidant activity and a stronger effect in reducing triglycerides and HDL-cholesterol. In addition, studies have demonstrated that the polysaccharide can effectively inhibit a range of viruses, depending on the specific virus type and dosage administered [28].

The size, species, and general appearance of brown seaweeds vary greatly, but they are often colored brown by a pigment that is produced during photosynthetic processes. Common brown seaweeds include Fucus species, Zonaria species, and kelp like Laminaria pallida. Brown seaweed has three types of polysaccharides: fucoidans (FUC), laminarians, and alginate [16]. Alginates are made up of alternating blocks of α-l guluronic acid and ß-d mannuronic acid and are found in the intracellular matrix and cell walls of brown seaweed. Alginates, which swell in water, are a flexible material that can be utilized as a disintegrating agent in tablets or as a film by virtue of their interaction with divalent and trivalent cations. its properties are dependent on the monomer sequence. The primary polymer in brown seaweed that stores glucose is called laminarin, which has a wide range of documented bioactivities, including antioxidant and anti-tumor properties [19]. However, its primary industrial application is as a ligand for innate immune system pattern recognition receptors [18]. FUC, a complex, heterogeneous sulphated polymer made of l-fucose and sulphate ester groups with trace amounts of other molecules such (acidic-)/monosaccharides, proteins, and acetyl groups, is another polymer that may be isolated from brown seaweed. The polysaccharide's content and properties are significantly influenced by the species, time of year, place of origin, and extraction technique. However, due to its potential anticancer, antiviral, anticoagulant, and anti-inflammatory effects, it is mostly utilized in biomedical-related domains. Seaweed also contains colors, phenolic compounds, fatty acids, sterols, alkaloids, terpenes, and halogenated chemicals [21].

3.2 Active packaging

The term "active packaging" pertains to a system in which the product, container, and surrounding environment work in concert to prolong the product's shelf life, enhance safety measures, retain sensory characteristics, and uphold the product's quality. The product is comprised of constituents that promote the movement of substances between the product and the environment, the packaging, and the product itself. The method by which food contact materials are produced utilizing seaweed (Figure 1). A monolayer system integrates the active component into the polymer, whereas a multilayer system controls the release of the active chemical by enclosing it between the polymer layers [33]. Methods such as chemical addition and temperature control are crucial for this procedure. Several advanced food packaging systems have been developed in recent times, such as ethylene scavengers, moisture management packaging, carbon dioxide generating systems, oxygen scavengers, and flavor and odor absorbent packaging. Table 2 presented the current applications of active packaging.

Table 2. Current applications of active packaging.

Packaging type	Active Compound	Packaging Structure	Improvements	Ref
Ethylene scavenger	Potassium permanganate	An ethylene scavenger supported by sepiolite, utilizing potassium permanganate as its main component.	Protract the maturation of recently harvested apricots, as well as potentially other fruits sensitive to C_2H_4, thereby extending their ability to be stored after harvest and enhancing	[34]

			their appeal to consumers.	
Oxygen and volatile organoleptic compound scavenger	Silica gel	NS	Decreased spoilage and disease rate. Chlorophyll content loss can be delayed by up to 8 days when stored at temperatures ranging from 29.4 to 33.2 °C and relative humidity levels of 68 to 73%.	[35]
	Vermiculite	Sachet	Delayed softening of the pulp and degradation of vitamin C. The temperature will be maintained at 25 degrees Celsius with a relative humidity of 54% for a duration of 5 days.	[36]
	Halloysite nanotube	LDPE Film	The elongated shelf life of tomatoes and bananas when they are preserved at a temperature of 4 °C and packaged in films.	[37]
	Zeolite-based minerals	LDPE film	The shelf life can be extended up to 20 days at a temperature of 4 °C by creating a balanced atmosphere, resulting in improved sensory quality.	[38]
	TiO_2	Chitosan film	The quality of the tomatoes was compromised and the maturation process was prolonged when they were stored at 25 °C and 50% relative humidity.	[39]
Oxygen scavengers	Potassium sorbate and sodium benzoate and	Chitosan, Pullulan, and Pectin and are utilized as edible coatings.	Strawberries have been found to be efficacious in mitigating weight loss, averting fruit softening, postponing color degradation, and sustaining titratable soluble solids levels.	[40]
	BHT or Sesamol	(1) HDPE/HDPE (BHT)/EVA, (2) HDPE /HDPE (active)/ethylene-vinyl acetate (EVA), (3) LLDPE/HDPE (active)/HDPE	A method that prevents lipid oxidation in linoleic acid and breakfast cereal in an effective manner.	[41]
	Hesperidin Pickering	Gelatin film that has been activated	The encapsulation of hesperidin resulted in	[42]

	emulsion with chitosan nanoparticle stabilization		improved compatibility and enhanced antioxidant activity prior to its incorporation into the film.	
	Carum copticum EOs and *Origanum vulgare* ssp. gracile	Two-dimensional lignocellulose and chitosan/cellulose nanofibers.	The active film displayed notable antioxidant and antimicrobial characteristics, thereby indicating that CNF and LCNFa have the capacity to control the release of bioactive compounds from the films.	[43]
	Iron-based	Utilizing iron-based oxygen scavengers in modified atmosphere packaging	Minimization of microbial and oxidative alterations in chicken thigh meats	[44]
Antimicrobial packaging	Lythrum salicaria extract	Cellulosic nanomaterials	The preservation of the effectiveness of antimicrobial nanoparticles or antimicrobial enzymes during immobilization without any substantial decrease.	[45]
	Tea tree oil (TTO)/β-CD complex	Poly(ethylene oxide) (PEO)	Both the efficacy of the antibacterial agent release mechanism from PEO nanofibers and the antibacterial activity exhibited by PEO nanofibers were enhanced. Escherichia coli demonstrated the most significant antibacterial effectiveness.	[46]
	Copaiba oil	Pectin/Nanoemulsion	The nanoemulsion that was formed demonstrated remarkable compatibility between the oil and the matrix of the film. Antimicrobial efficacy against *Staphylococcus aureus* and *Escherichia coli* has been enhanced.	[47]
	Cumin EO	Sodium caseinate/TiO_2 NPs 3D guar gum	The incorporation of both titanium dioxide (TiO2) and cumin essential oil (EO) led to a synergistic enhancement in the	[48]

		mechanical, barrier, and antimicrobial characteristics of the films.	
Nisin	Starch/ Halloysite nanotubes 1D	The film experienced a reduction in size and an enhancement in its ability to kill microorganisms in the presence of halloysite.	[49]
Oregano essential oil in a capsule	The research centers on the application of complex coacervates composed of soluble soybean polysaccharide and acid-soluble soy protein for the purpose of stabilizing Pickering emulsion, which is generated by films of soluble soybean polysaccharide.	The immobilization and improved retention of essential oil (EO) within the film matrix were outcomes of the encapsulation process, which produced films with sustained antimicrobial activity.	[51]
Cinnamon EO	Zein/Chitosan NPs 3D	The coexistence of CEO (chief executive officer) and CSNPs (chitosan nanoparticles) led to enhanced inhibitory effects on E. coli and S. aureus bacteria. This was a result of the enhanced transportation of essential oil (EO) by loading it into colloidal silica nanoparticles (CSNPs).	[51]

Antimicrobial packaging reduces, prevents, or delays the proliferation of microorganisms through the use of antimicrobial compounds on or within food packaging. This results in a prolonged pre-microbial development period and a deceleration of microbial multiplication [41]. Antimicrobial packaging comprises four distinct categories: antimicrobial coating, antimicrobial sachet or pad, intrinsically antibacterial polymer, and direct incorporation in polymer. Moisture-controlling packaging can be categorized into two distinct types: RH controllers, which eliminate humidity from the air within the packaging, and moisture absorbers, which absorb liquids within the packaging. The former are frequently utilized in the production of dehydrated food items, including candies, snacks, and almonds. Desiccants including calcium oxide, silica gel, and inorganic salt mats are also incorporated. Pads, linens, and blankets comprise moisture absorbers, which are composed of two layers: a microporous polymer, such as polyethylene, is positioned atop a highly absorbent polymer, such as granules, which flow readily [45]. These are utilized for the purpose of controlling the amount of liquid present in packaged goods, fish, poultry, and produce.

Ethyene, a small molecule, acts as a growth-promoting hormone, accelerating the ripening of fruits and vegetables. Consequently, leafy greens experience a reduced postharvest shelf life, increased food softening, and an accelerated rate of chlorophyll breakdown [49]. One possible approach to reduce the level of ethylene around the product (as shown in Table 2) is to use a sachet or blanket containing potassium permanganate. This

substance acts as an oxidizing agent and deactivates ethylene when it comes into contact with inert minerals that are immobilized. Amines, aldehydes, and sulphides may arise as a result of protein and other organic compounds breaking down during the preservation of food items like fish and poultry. One can selectively collect these volatile molecules to prevent the mixing of odors from different products during transportation. The packaging, which is resistant to odors, utilizes polyethylene terephthalate, a permeable port, and an odor-absorbing sachet containing nickel and charcoal. To eliminate amines produced during the degradation of protein in fish packing, one can add citric acid or other acidic substances to the polymer film [51].

3.3 Utilizations of seaweed in food packaging

The potential hazards associated with the use of chemicals as active agents in packaging stem from their capacity to migrate from polymers to food. As a result, scientific inquiry is placing an increasing amount of emphasis on the utilization of natural substances rather than chemical active agents. Seaweeds are regarded as prospective basic materials or active constituents on account of their copious polysaccharide content. They enhance the functionality, sustainability, and sensory attributes of the product when blended with any biodegradable polymer, thereby surpassing the performance of conventional materials. Potential applications for seaweeds include the manufacture of sachets, biodegradable plastics, sustainable packaging, consumable packaging, and active packaging [52]. The most recent applications of seaweed polysaccharides as packaging material were detailed in Table 3.

Table 3. Recent application of seaweed polysaccharides on packaging material.

| Type Of Application	Polysaccharides	Characteristics of the Packaging Material	Packaging Matrix	Reference
Smart and intelligent packaging	κ-Carrageenan, agar	Enhanced UV–visible light obstruction, pH responsiveness, and physical characteristics. Visual color changes were observed in the films used for the buffer solution (pH 2.0–12.0), ammonia vapor (80 M), and pork spoilage studies.	*Clitoria ternatea Linn*, nano-ZnO, and Nano-TiO$_2$	[53]
Smart and intelligent packaging	Carrageenan	Enhanced UV protection without diminishing film transparency. A remarkable color change that is pH-responsive across a broad pH range of 2–12. Effectively monitoring the freshness of packaged milk was intelligent film.	Propolis, Shikonin, and Gelatin	[54]
Smart and intelligent packaging	κ-Carrageenan	Enhanced capacity to retain water vapor and block UV–visible light. Enhanced antioxidant and pH-responsive characteristics. Can be utilized for	Mulberry polyphenol extract	[55]

		monitoring the perishability of milk.		
Active packaging	*Fucus vesiculosus*	Enhanced the dimensions, resistance to stretching, and ability to withstand deformation. Prevent the oxidation of lipids in packaged poultry meat for a minimum of 25 days during storage.	Whey protein	[56]
Active packaging	Gelidium sesquipedale	Improved characteristics for the integration and liberation of biologically active extracts.	Nanocellulose, Polyvinyl alcohol,	[57]
Active packaging	Sodium alginate	An elevation in fracture strain. Moisture content, water vapor permeability, and oxygen permeability have all increased. Effective against *S. aureus* and *E. coli*.	Pyrogallic acid, $CaCl_2$, Carboxymethyl cellulose	[58]
Active packaging	Furcellaran	Elevated dimensions, moisture level, and resistance to stretching. Observations were made regarding the variations in color under different pH conditions. Significant levels of antioxidant activity.	Rosemary extract/Gelatin hydrolysate	[59]
Active packaging	Sodium alginate	By means of microencapsulation, lemon grass oil can be released under precise control. The films demonstrated inhibitory effects on the proliferation of *L. monocytogenes* and *E. coli*.	Lemongrass oil	[60]

By incorporating nanocrystalline cellulose, the mechanical properties, thermal stability, tensile strength, and elastic modulus of biodegradable nanocomposites fabricated from alginate were all improved. Furthermore, the research documented a reduction in swelling properties, water vapor permeability, and elongation at break. However, an investigation that examined the incorporation of agar and nanoclay into a film intended for biodegradable food packaging revealed that both the swelling ratio and tensile strength were enhanced [53]. Additionally, its solubility in water, the angle of surface contact between water and the substance, and the rate of water vapor permeation were all diminished. As a consequence of integrating lemongrass essential oil and alginate into the packaging film for fresh cut fruit, weight loss, color alteration, and respiration rate were all reduced. Furthermore, negligible alterations were observed in the physical and sensory attributes, accompanied by minimal quantities of microbial activity [58]. Furthermore, the results obtained from employing a salted alginate film in microwaveable packaging revealed an improvement in heat dispersion and the film functioning as a conductor throughout the heating process. To determine the bactericidal effect of a mixture of carrageenan, locust bean gum, and organically modified nano-clay against L. monocytogenes, an investigation was undertaken. The primary aim was

to increase the longevity of culinary products. Furthermore, it resulted in increased tensile strength, delayed thermal degradation, elongation at the point of fracture, and level of aggregation. An additional investigation revealed that the amalgamation of carrageenan and grapefruit seed extract demonstrated enhanced characteristics in terms of water vapor permeability, elongation at break, and UV barrier properties. Additionally, the results revealed a significant reduction in tensile strength, elastic modulus, and water contact angle, in addition to noteworthy antibacterial effectiveness, particularly against gram-positive bacteria [60].

3.4 Impact of seaweed integration on the characteristics of film, including antimicrobial and antioxidant properties

The mechanical, thermal, optical, and chemical properties of other polymers are altered when seaweed is added. To produce a packaging that is both safe and effective, it is necessary to thoroughly assess these effects, which are depending on the seaweed polysaccharides that were added. The type of seaweed polysaccharide being included and the polymer in which it will be incorporated are both important factors in determining the results [57]. Chemical characteristics like hydrophobicity or hydrophilicity, as well as the film's composition with functional groups, are crucial in determining how safe and effective food packaging is. Because of the various components and how they interact, the integration may vary greatly. After adding the agar to the SPS, Fourier transform infrared (FTIR) spectroscopy was used to look for changes in the functional groups in the film (Fig. 2) [58. Little peak shifts to lower wave numbers were observed, but there were no appreciable alterations in the recorded peak as shown by the spectra. Increased intermolecular hydrogen bonding is shown by these, suggesting that the two components are compatible and interact. One possible explanation for the increased moisture absorption of the film upon agar insertion could be its higher hydrophilicity as a sulphated polysaccharide. Overall, these investigations demonstrate that the most frequent modification in chemical characteristics following the seaweed addition was an increase in hydrophilicity. Seaweeds' anionic nature causes greater absorption of moisture, swelling, and a decrease in water contact angles. Nonetheless, the findings demonstrate that variations in crystallinity are influenced by both the seaweed and the way the polymer and polysaccharide interact.
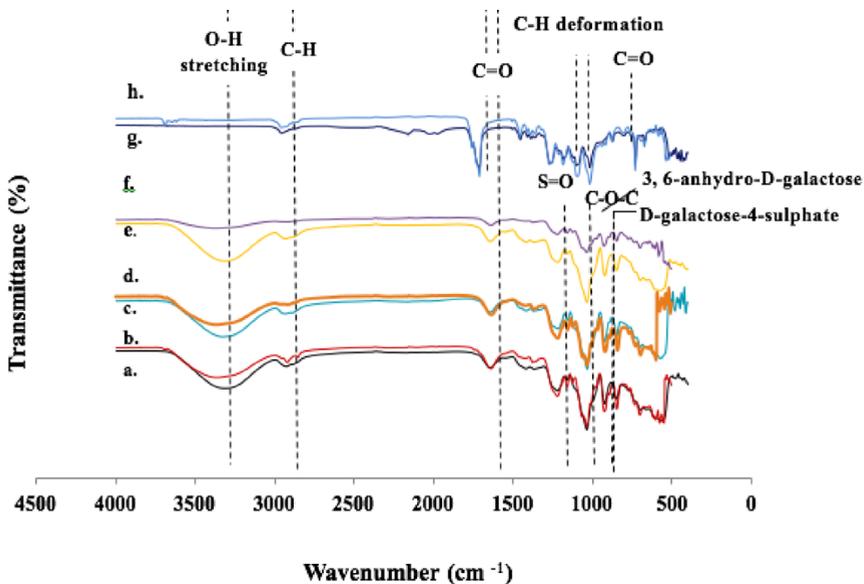
Fig. 2. An analysis was conducted on the Fourier transform infrared (FT-IR) spectra of seaweed-based films, which incorporated additives and conventional mulch film, both prior to and subsequent to their burial in soil [61]. (Copyright Of The MDPI).

It is challenging to speculate on the morphological alterations that may result from the incorporation of components, such as seaweed polysaccharides, because much depends on the interaction between the polymer and the seaweed [62]. Nevertheless, it is critical to examine them due to the fact that the amalgamation of diverse materials might give rise to voids and induce additional modifications that have the potential to impact technical characteristics. The effect of monomer arrangement on the physical properties of alginates has been demonstrated. Alginate's strong affinity for multivalent cations, which causes the formation of gels, and its ability to transition between a sol and gel state irrespective of temperature are its primary physical characteristics. The surface morphology of agar films with different concentrations of agar and sugar palm starch was analyzed using SEM. After agar was added to the mixture, the SEM image revealed a smooth and homogeneous surface devoid of any concentrations or phases of sugar palm starch, according to the study. This finding suggests that the two constituents of the film are harmonious and operate efficiently when combined [63]. On the other hand, breaking structures emerged on the surface as the Agar concentration rose. This could be because to increased filler content in the film matrix and polymer bonding. The morphological alterations brought about by the addition of esterified alginate to the Polyhydroxy butyrate mix were examined using SEM analysis of Polyhydroxy butyrate film samples. The inclusion of polysaccharide caused a modification in the morphological composition of the Polyhydroxy butyrate blend, displaying an exposed, uneven, and dense surface texture. The surface morphology of a film made of sodium alginate and polyvinyl alcohol was analyzed [64]. The analysis of the SEM image demonstrated that the blend film exhibited a uniform texture, suggesting excellent miscibility and the absence of phase separation.

In the context of food packaging, polymer films that possess the appropriate mechanical properties include elongation at break, elastic modulus, and tensile strength. The tests demonstrate that the film can withstand a range of stresses, including those encountered in the preparation, handling, and storage of food, without experiencing any degradation in its integrity [65]. Intermolecular interactions between polymer chains, as well as the integrity and solubility of the constituents, have a substantial impact on the mechanical properties of composite films produced by combining. On the subject of mechanical properties, seaweed polysaccharides have been the subject of numerous investigations. In approximately 50% of the examined studies, the integration of seaweed polysaccharides into the appropriate polymer resulted in an increase in tensile strength. The utilization of flour and alginate in the production of food packaging films with remarkable mechanical properties [66] was observed. Alginate and other agar or starch-based films demonstrate remarkable mechanical properties.

The melting temperature (Tm) and glass transition temperature (Tg) are crucial thermal parameters that reflect the level of intermolecular bonding among polymer chains. They are also required to offer information that must be taken into account during the process and determine whether the polymers are appropriate for use in food packaging [67]. Following the seaweed's addition, collagen with fucoidan added showed better thermal characteristics (Fig. 3). The constituents of the mixture exert a substantial impact on the manner in which the incorporation of seaweed influences the thermal properties. Varying degrees of miscibility, crystallinity, and overall interaction can have significant impacts on the temperature at which crystallization and melting take place.
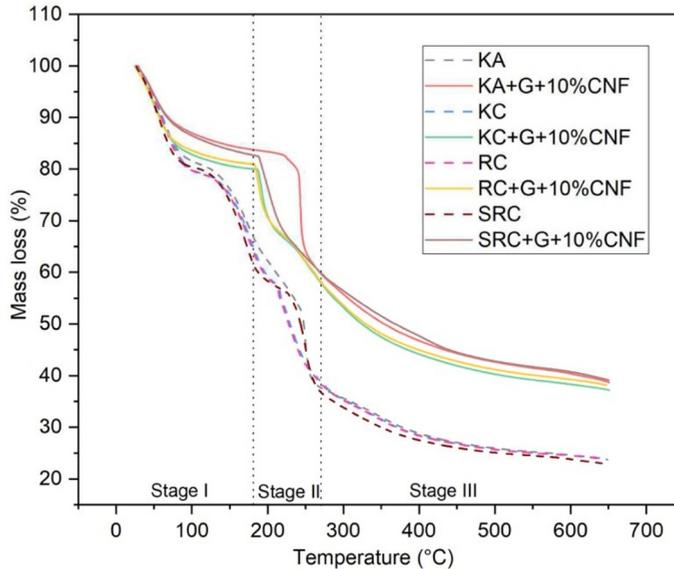
Fig. 3. Thermogravimetric analysis (TGA) was conducted on bioplastic film matrices derived from seaweed, which were loaded with cellulose nanofiber [68] (Copyright Of The MDPI).

Due to the fact that food safety is a major concern in the industry, antimicrobial packaging is indispensable for active packaging. Fundamental to ensuring the sustainability and safety of packaging is the incorporation of natural antimicrobials like chitosan. Considerable research has been devoted to the examination of carvacrol, durian starch, and carrageenan films. The inclusion of purified saccharides, including carrageenan and alginate, in a polymer film exhibited minimal or no inhibitory impact on L. monocytogenes and E. coli bacteria [54]. *S. aureus* was not inhibited by the durian starch/carrageenan control films, as determined by the disk diffusion test. After pre-diffusing the film with 10% carvacrol for 24 and 48 hours, all gram-positive bacteria were completely suppressed. Furthermore, the introduction of nano-clay or nano silver did not result in any antibacterial properties in the carrageenan-based composite film when tested against L. monocytogenes or E. coli. Another investigation [55] found that an agar blend containing both gram-positive and gram-negative food-borne pathogenic bacteria did not demonstrate any antibacterial properties. The addition occurred only after a combination of six unique copper nanoparticles with strong antibacterial properties was introduced.

Lipid oxidation significantly affects food and food product quality. Oxidation produces agents like free radicals, which are cytotoxic, carcinogenic, and mutagenic, and can lead to serious health issues [58]. Foods that have experienced lipid oxidation may also have less nutritional value and a shorter shelf life. Antioxidant packaging is intended to reduce the degree of protein breakdown and lipid oxidation that occurs inside the packaging. Antioxidant-containing active packaging is a viable substitute for conventional packaging, which incorporates or coats the film with antioxidants. The trend toward fewer synthetic additives in packaging has increased interest in natural antioxidants like plant extracts and essential oils because they are safer and have more health advantages [53]. To summarize, the findings suggest that a wide range of polysaccharides possess antioxidant activity to different extents. This information holds potential for the formulation of packaging containing antioxidants. To bolster the antioxidant properties and prevent lipid oxidation

while increasing food safety, it is feasible to integrate substances such as mulberry extract and plant essential oils for this purpose. Additional research is necessary to ascertain the antioxidant properties of various extracts and polysaccharides derived from seaweed. This is crucial for the successful application of seaweed as an antioxidant agent in active food packaging [52].

4 Conclusion

Seaweed integrated into natural polymers holds significant potential to revolutionize food packaging in response to increasing consumer awareness of sustainable alternatives. Reducing the use of synthetic packaging could potentially result in a decrease in the level of plastic pollution in our environment. Seaweed possesses antibacterial and antioxidant properties that have the potential to extend the shelf life of food and decrease food waste resulting from decomposition. Further investigation is necessary in order to determine the precise influence of seaweed on the shelf life of particular food items. To optimize safety and mitigate potential hazards linked to seaweed utilization, it is critical to strengthen current regulations concerning the accumulation of toxic metals and other potentially hazardous substances. This will facilitate the broader incorporation of seaweed in food products and packaging materials. To customize the mechanical characteristics of the film for a specific application, a polymer blend or natural plasticizer can be employed. All things considered, it appears to be a viable option for more active and sustainable movies with space for development. Seaweed is being used to create biodegradable packaging that is more practical and significant than existing techniques, which has prompted greater study into process optimization to make seaweed a potential rival in the market. Furthermore, because seaweed has mechanical, antibacterial, antioxidant, and releasing qualities, more thorough research should be done to determine which particular areas will benefit most from seaweed's advantages over conventional packaging materials. A more sustainable approach to food packaging also requires improving the current polysaccharide membranes through the use of additives like lipids, other polymer blends, and a greater range of potentially changed polysaccharides.

Acknowledgment

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