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Seaweed-based films for sustainable food packaging: properties, incorporation of essential oils, applications, and future directions

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ABSTRACT

Seaweed-based films have emerged as a promising solution for sustainable food packaging due to their renewable sourcing, biodegradability, and functional properties. This review provides an in-depth analysis of seaweed-based films, focusing on their properties, incorporation of essential oils, applications in food packaging, and future directions. The advantages of seaweed-based films include their renewable and abundant source, biodegradability, and favorable barrier properties. The review explores the physical and mechanical properties, barrier properties, and safety considerations of seaweed-based films. Additionally, it discusses the incorporation of essential oils into seaweed-based films and their potential benefits. Current and potential applications of seaweed-based films in food packaging, ranging from fresh produce to dairy products, are examined, along with the advantages and challenges associated with their use. A comparison with other sustainable packaging options is provided. Furthermore, the review highlights future research directions in developing seaweed-based films, such as improving mechanical properties, extending shelf life, scaling up production, reducing costs, and innovation in formulation. Overall, seaweed-based films offer a promising and sustainable alternative for food packaging, with ongoing research and development driving their advancement and potential for a more environmentally friendly packaging industry.

Keywords: seaweed-based films, sustainable packaging, food packaging, biodegradability, renewable sourcing, barrier properties, essential oils

INTRODUCTION

The growing need for sustainable packaging has become increasingly apparent in recent years. With environmental concerns such as plastic pollution and climate change at the forefront, there is a pressing demand for innovative packaging solutions that minimize negative impacts on the planet. One promising approach is using edible films and coatings, offering functional and sustainable benefits.

Edible films and coatings are thin layers of materials that can be consumed with packaged food or easily removed before consumption. They provide a protective barrier against external factors such as moisture, oxygen, and microbial contamination while also extending the shelf life of perishable products. These films can be made from various natural sources, including proteins, polysaccharides, lipids, and composite materials **[1]**.

Among the different types of edible films, seaweed-based films have gained significant attention as an environmentally friendly option. Seaweed, a type of marine macroalgae, possesses unique properties that make it well-suited for sustainable packaging applications.

One of the key advantages of seaweed-based films is their renewable and abundant source. Seaweeds are fast-growing marine plants that can be cultivated without arable land, freshwater, or pesticides. They have a high growth rate, allowing for sustainable harvesting without depleting natural resources. This makes seaweed an attractive alternative to traditional packaging materials derived from fossil fuels or limited resources **[2]**. Furthermore, seaweed-based films offer inherent biodegradability and compostability. Unlike conventional plastic packaging, which can persist in the environment for hundreds of years, seaweed films can naturally decompose through microbial activity, contributing to a more circular economy. This feature aligns with sustainable packaging principles, where materials should have minimal environmental impact at the end of their life cycle **[3]**. In summary, seaweed-based films offer a range of advantages for sustainable packaging. They are derived from renewable resources, biodegradable, and exhibit favorable barrier properties. Using seaweed as a packaging material, we can reduce reliance on fossil fuel-derived plastics and contribute to a more environmentally friendly packaging industry. The following sections will explore the properties of seaweed-based films in more detail and discuss their potential applications in food packaging **[4]**. Additionally, the review will assess the current and potential applications of seaweed-based films in food packaging. From extending the shelf life of fresh produce to enhancing the preservation of meat and dairy products, seaweed-based films offer a versatile and sustainable packaging solution across various food categories. The advantages and challenges associated with using seaweed-based films in food packaging will be analyzed, along with a comparison to other sustainable packaging options **[2]**.

Finally, the review will identify future research directions in developing seaweed-based films and provide a comprehensive conclusion summarizing the key points discussed. By examining the potential of seaweed-based films for sustainable packaging, this review aims to contribute to the ongoing efforts to reduce the environmental impact of packaging materials in the food industry **[4]**.

Properties of Seaweed-Based Films

In recent decades, scientists have discovered an abundance of unique compounds in marine (often termed the mother of the genesis of life) species that show promise as constituents in newly developed medicines, foods, packaging materials, and textiles that may be used to promote wellness for people. The term "seaweed" describes a wide variety of macro or multicellular marine plants and algae found in the ocean, rivers, ponds, and other bodies of water **[5]**.

Plastic is one of the most popular materials because of its many applications, long lifespan, high resilience, and relatively inexpensive cost **[6]**. However, regular plastics harm marine ecosystems since they are produced using non-renewable resources **[7]** **[8]**, **[9]**, **[10]**. Bioplastics might solve these issues; however, biomass-based first and second-generation bioplastics significantly influence land-use change, directly and indirectly **[11]**, **[12]**. As for bioplastics, seaweed is known as a 3rd generation feedstock because it requires no additional land for growth **[13]**, **[14]**. The composition of seaweed (Chemical) includes minerals ranging between 7 to 37.5%, water ranging starting from 80% and uptake of 90%, protein constitutes between 3 and 14.5%, carbohydrates present up to 50%, and Lipids constitute 1 to 3% **[15]**, **[16]**. Types of seaweeds are demonstrated in Figure 1.

Seaweed has been used extensively in bio-packing, food, and biomedical applications because of its biocompatibility, bio-absorbability, biodegradability, and nontoxicity. Both enzymatic association and non-enzymatic degradation of these polymers are possible. Alginate, agar, and carrageenan are three hydrocolloid polysaccharides produced from seaweed that have several uses as biopolymeric films **[17]**. Carbon and nitrogen cycling are only two examples of the ecological benefits and ecosystem provisioning that may be gained through seaweed agriculture. Thereby perhaps aiding the fight against eutrophication, ocean acidification, and climate change **[18]**, **[19]**.

Due to their excellent effects on ecological concerns and other distinctive qualities, materials that come into touch with food have great potential to benefit from fresh creative technologies like edible films. Biopolymers derived from seaweed have shown promise as a high-quality and reasonably priced alternative to petroleum-based polymers. Essential oils (EOs) are a natural, non-toxic alternative to synthetic preservatives that may be used to enhance the functioning of biopolymer-based packaging. Food packaging prevents food from spoiling due to environmental causes, especially when bioactive chemicals like EOs are included in biodegradable packaging materials **[20]**.

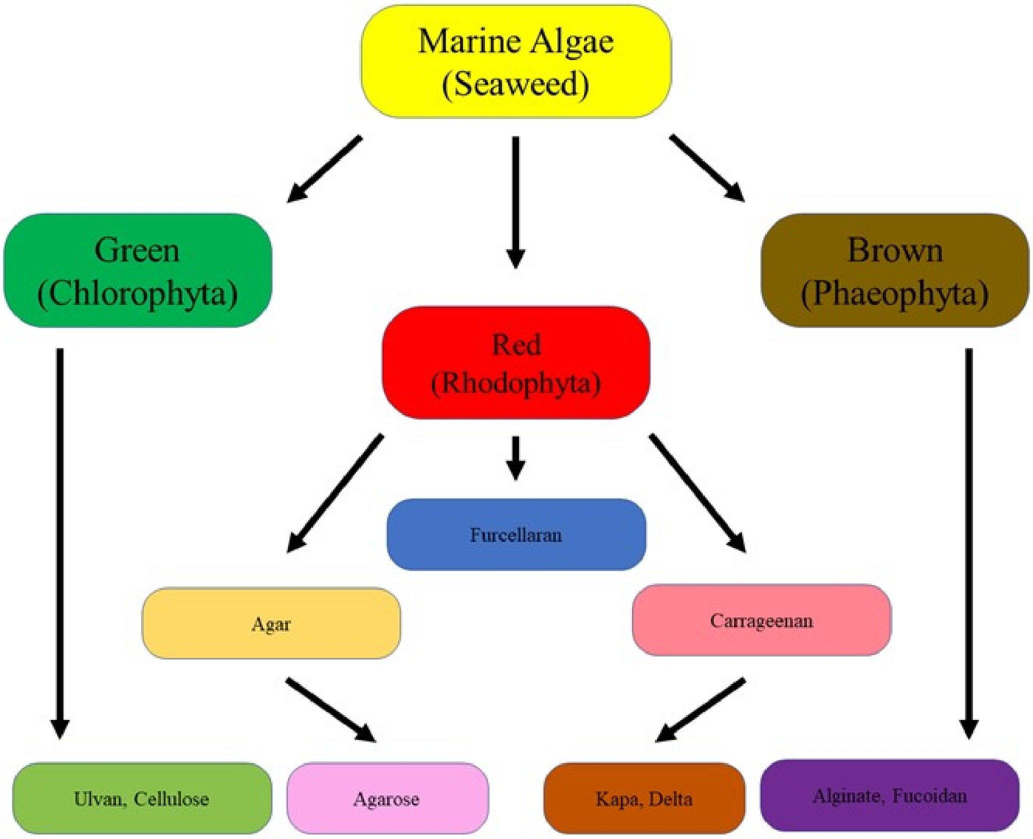

Figure 1 Overview of Seaweed.

Growing seaweeds is frequently seen as a way to address problems with food security, such as climate change, a lack of arable land, food scarcity, and wasteful fertilizer usage. The future bio-economy might benefit significantly from a thriving seaweed sector since it would allow for more efficient food production, new goods, and employment creation. With an average selling price of USD 0.48 per kg for brown seaweed, USD 0.40 per kg for red seaweed, and USD 0.80 per kg for green seaweed (all wet weight), seaweed farming accounted for approximately 31% of the entire approximately 120 million tons of aquaculture sector output (35.5 million tons) in 2019. More than half of all harvested seaweed is utilized to make hydrocolloids, whereas only around half is consumed by humans. About 30 MM tons of seaweed are eaten annually for various uses, including the food and pharmaceutical industries, giving rise to a worldwide seaweed market worth about USD 11 billion annually. The price of seaweeds is predicted to rise further in the near future **[21]**, **[22]**, **[23]**.

As a possible bioresource, seaweed has been the subject of recent research and discussion among bioplastics. Alginate has been studied by Rinaudo **[24]** as a potential solution for food packaging and more recently, in addition to alginate, Carina and Sharma **[2]** use polysaccharides as food packaging material isolated from different seaweed to further the current research on seaweed. The overall polymer condition of seaweed and its characteristics to form various plastic kinds are described by Zhang and Show **[25]**, Pacheco and Cotas **[26]**. Seaweed polymers are extracted and reviewed by Shravya and Vybhava Lakshmi **[27]**, Lim and Yusoff **[28]** for application in bioplastic manufacturing. Experimental research on the manufacture of seaweed-based polymers has been conducted in certain studies.

Albertos and Martin-Diana **[29]**, Aragão Rebouças Júnior and Turan **[30]**, Lim and Hii **[31]** tried out making edible films out of red and brown seaweed, brown seaweed alginate-based bioplastics. These studies review the various types of seaweed-based plastics. However, they seldom analyze the manufacturing and end-of-life (EoL) implications on the environment quantitatively, instead focusing on the physical qualities and prospective techniques to create seaweed-based plastics, with some even employing experimental data. Ayala and Thomsen **[32]** explore the potential for recycling some biorefinery byproducts for film production and the consequences on the environment of a novel seaweed-based plastic manufactured from *Saccharina latissima*. Carbon balancing and life cycle assessment are used to evaluate this possibility. A summary of edible packaging based on of seaweed biopolymers is provided in Table 1.

Previous research by Zhang and Thomsen **[33]** has highlighted the significance of maximizing the value of the complete seaweed biomass. That is significant from both an ecological and a monetary viewpoint. In the food industry, where biomass has a high economic value, there is a considerable demand for seaweed biomass. Since seaweed biomass is used at a far lower cost in plastic manufacture, its value rises when it is put to good use, including byproducts from bio-crude extraction **[34]**.

Seaweed-based films are highly biodegradable, meaning they can be naturally broken down by environmental microorganisms **[35]**. They offer an eco-friendly alternative to conventional plastic films that often persist in the environment for extended periods. Seaweed is a renewable resource that can be sustainably harvested, making seaweed-based films a sustainable choice **[36]**. This characteristic aligns with the principles of environmental conservation and resource efficiency. One unique property of seaweed-based films is their water solubility **[36]**. This characteristic makes them suitable for single-use applications, such as dissolvable packaging units for detergents, personal care products, or food items.

Seaweed contains natural compounds, such as alginates and polyphenols, which exhibit antimicrobial properties **[35]**. When incorporated into seaweed-based films, these compounds can help inhibit the growth of bacteria and fungi, making them useful for food packaging where microbial spoilage is a concern. The versatility of seaweed-based films allows for modifications through blending with other biopolymers or incorporating additives **[36]**. This flexibility enables the films to be tailored to specific requirements, such as mechanical strength, gas permeability, or moisture resistance. So, seaweed-based films offer a sustainable and biodegradable alternative to conventional packaging materials. Their properties, including biodegradability, barrier properties, flexibility, water solubility, antimicrobial properties, and versatility, make them a promising solution for reducing plastic waste and environmental impact in various industries.

Table 1 Summary of edible Packaging based on of seaweed biopolymers.

Derivative	Biopolymer	Application	Ref
Gelidium sesquipedale	Agar	Active Pack	**[37]**
Kappaphycus sesquipedale	Carrageenan	Edible coating	**[38]**
Laminaria sesquipedale	Alginate	Edible coating	**[39]**
	Sodium alginate	Packaging	**[40]**
	Chitosan	Edible coating	**[41]**
Furcellaria lumbricalis	Furcellaran	Packaging film	**[42]**

Mechanical Properties

Food packaging films must meet strict standards for mechanical properties such as tensile strength, modulus of elasticity, and deformation upon break. The results of these tests reveal how well the film maintains its structural integrity under the numerous pressures that arise during the preparation, transportation, and storage of food in packaging. The elastic modulus measures the force per unit area required to stretch a film sample to a certain size. Measured in terms of force per unit area, tensile strength may be used to evaluate the resistance of a film to tearing. And the proportion of change in running time due to a break is given by the elongation at the break **[43]**.

PVA and sodium alginate were combined to create the new substance. A universal tensile machine was used to analyze the samples' tensile properties, with the crosshead moving at a rate of 50 mm/min. Each sample had an initial length of 40 mm, a breadth of 10 mm, and a 100-150 m thickness. The results showed that the tensile modulus was increased by 210 MPa (from 510 MPa to 700 MPa) when PVA and SA were used together. The addition of the polysaccharide resulted in a modest improvement in tensile strength from 41 MPa to 44 MPa and an increase in elongation at break from 53% to 57%. The rigid polysaccharide added to the polymer mix decreased its flexibility, but the study found that it was still useful for most applications despite this **[44]**.

Jumaidin and Sapuan **[45]** in terms of research towards making an environmentally friendly agar film with varying amounts of agar. Tensile strength was measured with the crosshead moving at 4.5 mm/min at 22 °C and 51% RH relative humidity. Tensile strength increased from 10.5 MPa with no agar to 14.5 MPa with 32% agar and 13.5 MPa with 42% agar. Also, the tensile modulus rose progressively from 1500 MPa at 0% agar to 2000 MPa at 42% agar. The elongation at break was similarly affected by the incorporation of agar into the SPS, going from 2% at 0 .1wt% agar to 0.77% at 41 wt% agar. SPS and agar may be readily miscible owing to their same chemical structure and phase compatibility, which may explain the observed increase in tensile strength. The more complex network structure of agar explains why it has superior mechanical qualities versus SPS.

When it comes to evaluating film performance, mechanical qualities are just as critical as water barrier capabilities, particularly for packaging and plasticulture. Mulch film has to be sturdy enough to withstand the weight of the equipment used to lay it on the ground. Strong mechanical qualities are preferred to account for certain stress and deformation while handling and putting the films on the soil. The findings demonstrate notable distinctions between seaweed based-films and traditional mulch films. Films made from seaweed that was filled with commercial $CaCO_3$ had the highest TS, at 84.92%, followed by films made from seaweed that was filled with microbial-induced $CaCO_3$ (82.14%), the control group (72.73%), and the conventional mulch film **[46]**.

Mechanical parameters including tensile strength, modulus of elasticity, and stretch at break influence food packaging polymer film quality. The linkages and solubility of chemicals and intermolecular interactions between polymer chains during blending determine composite films' mechanical properties. Integrated chemicals may change the film matrix's structure, making it less dense and allowing components to interact beyond hydrogen interactions with water molecules. There have been a number of research looking at how adding seaweed polysaccharides affects mechanical quality. More than half of the trials found that adding seaweed polysaccharides to the matching polymer increased the material's tensile strength. Excellent mechanical qualities were achieved by using alginate and starch to create films for food packing **[47]**. Alginate-based agar films are mechanically strong **[48]**.

Thermal Properties

Seaweed may improve thermal characteristics, but how much depends on the other ingredients in the mixture. The impacts on melting and glass transition temperature might vary greatly due to varying degrees of miscibility, crystallinity, and overall interaction. Adding FUC to collagen enhanced the material's thermal characteristics, while adding alginate to PHB decreased them. However, the alginate/PHB mix exhibited no changes in thermal properties **[2]**.

Understanding how polymer chains interact can be gleaned from their thermal properties, including parameters like melting temperature and glass transition temperature. These properties play a vital role in determining the suitability of polymers for applications like food packaging. They offer valuable insights that guide the entire process **[49]**. Thermal analysis by Goonoo and Bhaw-Luximon **[50]** has shown that carrageenan containing blends are somewhat miscible in the amorphous areas but not the crystalline portions. This causes the crystallization temperature to rise and the enthalpy of crystallization to fall, both of which were previously greater in the KC/PHBV mix.

According to X-ray diffraction and differential-scanning calorimetry, adding sodium alginate to PVA film lowered the melting temperature **[44]**. Alginate inclusion into PLA did not affect thermal characteristics **[51]**. The addition of alginate to PHB decreased the thermal stability **[52]**. When combined, adding agar and sugar palm starch increased the glass transition and melting temperatures **[45]**. Different change in properties of films by incorporating seaweed is given in Table 2.

Table 2 Change in properties of polymer film by incorporation seaweed.

Source	Increase/Decrease in different properties	References
Allyl isothiocyanate	coating and gas barrier properties	**[53]**
Chitosan	flexibility, permeability and hydrophobicity	**[54]**
Alginate	homogeneous, lower moisture, light absorbance, respiration rate, thermal properties, heat distribution	**[55]**, **[56]**, **[57]**, **[58]**
Bio-nano composite film	tensile strength, water resistance, thermal stability	**[59]**
Nanocrystalline cellulose	water solubility, water contact angle, elongation	**[60]**
Carrageenan	tensile strength, thermal degradation, uv barrier properties, moisture content, elongation, antimicrobial activity	**[10]**, **[61]**
Agar	tensile strength, the contact angle of water, swelling ratio	**[62]**
Polylysine	stronger complexes through electrostatic attraction	**[63]**

Biodegradability and Composability

Polymers' biodegradability is determined by three factors: (a) their chain length (i.e., molecular weight, (b) the complexity of their chemical formula, and (c) their crystalline structure **[64]**.

The extremely rapid breakdown is typical for simple, low-molecular-weight amorphous polymers. Compostability, on the other hand, is associated with improved biodegradation in specially controlled environments with the right combination of factors, such as high humidity and temperature and the presence of microorganisms **[65]**. Composting tests may last 180 days at a certain temperature **[66]**. Because composting produces material rich in nutrients, in contrast to landfills, which produce carbon dioxide and methane, It benefits society as a whole if we switch to biodegradable plastics instead of single-use ones. Plant-based biodegradable polymers retain their composability even after being tainted with food scraps, in contrast to traditional plastics, which lose their ability to be recycled and are instead thrown away in landfills **[67]**. Bio-based degradation of biopolymer is given in Table 3.

If microorganisms are present to help in decomposition, the compostability or biodegradability of a biopolymer will be enhanced. Different outcomes may be achieved via controlled (industrial facilities) and unmanaged (natural habitats; soil, water, landfill, compost) degradation techniques owing to differences in factors like UV light exposure and oxygen availability **[65]**.

Table 3 Bio Degradation of bio-based biopolymers.

Type	Biopolymer	Percentage of Biodegradable	Rank	Testing Environment	Reference
Bio-Based	Alginate	90	severe	compost	**[68]**
	PLA	84/10/13	severe/low/low	compost/soil/compost	
	PHB	79/64	severe/moderate	compost/soil	
	Chitosan	100	severe	aqueous	
	Starch Based	14	low	soil	
	PHA	48/5	moderate/low	soil/compost	

Essential oils (EOs) and seaweed-based films

Edible films made from seaweed are popular for food packaging due to their high quality and biodegradability. Essential oils (EOs), which have potent antibacterial and antioxidant properties, are often added to seaweed-based biopolymers to create functional and active packaging materials with improved performance, such as increased shelf life and enhanced nutritional characteristics. The production process of seaweed-based films incorporating EOs is illustrated in Figure 2. EOs can render seaweed films mechanically stronger, more water-repellent, more UVR-resistant, and more thermally stable **[20]**.

The use of EOs in food packaging has gained popularity as a natural alternative to synthetic preservatives. Adding EOs to the polymer matrix can allow for the slow release of these beneficial compounds into the packaged food, improving its quality and shelf life. Essential oils are complex compounds that can be extracted through distillation of plant material or mechanical processes. These molecules are small, volatile, and hydrophobic, with a molecular weight of less than 300 Da.

Edible films made from seaweed infused with essential oils have been developed for food packaging **[69]**. Wet processes provide films with higher transparency, homogeneity, and reduced WVP and opacity. Wet processes are commonly used to create films with high transparency and homogeneity and reduced water vapor permeability and opacity. The solvent casting method is the dominant wet film creation process, where film-forming chemicals are dissolved in a solvent, cast onto a plate, and dried to remove the solvent. Water, ethanol, acetic acid, and lactic acid are commonly used solvents for film formation. Film-forming compounds contain polysaccharides with hydroxyl and polar groups, which can bond through covalent, ionic, electrostatic, and hydrophobic interactions. Hydrogen bonding is crucial to polysaccharide film formation. The interactions between the film and food product depend on the film's thickness, structure, molecular weight, temperature, and production parameters **[70]**, **[71]**, **[72]**.

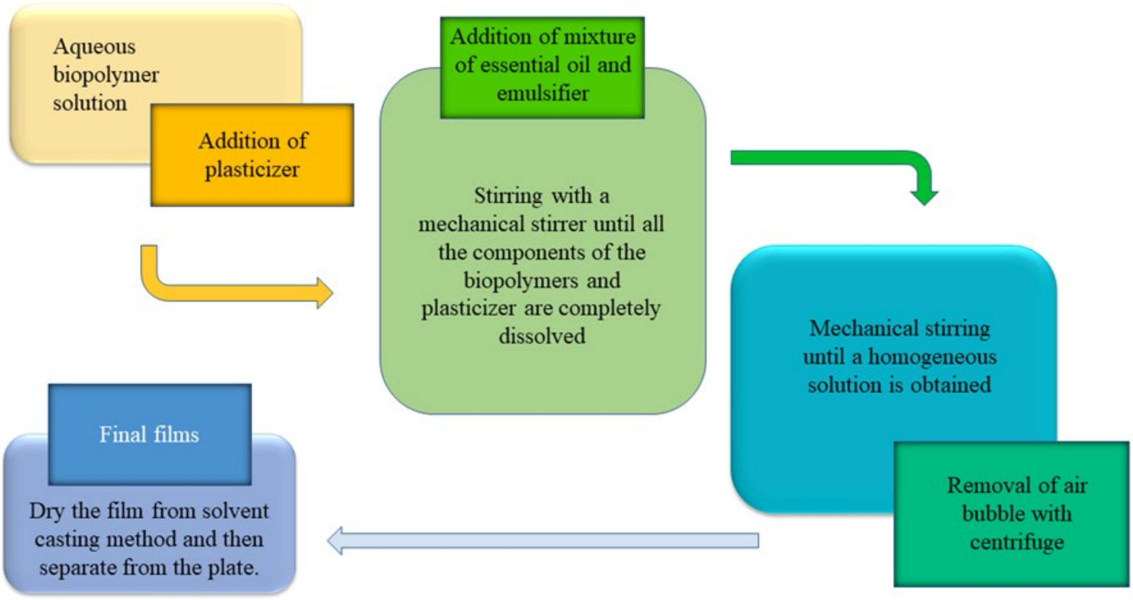

Figure 2 Overview of the production process of the seaweed-based film by incorporating essential oils.

Characterization of EOs loaded seaweed-based film

The seaweed biopolymer-based food packaging matrix containing EOs may be viewed by SEM, TEM, and AFM. Packaging materials' physical properties depend on the film's structure. The matrix must equally distribute antimicrobial essential oils (EOs) for the seaweed-based film toJ work. Seaweed polymer matrix-EO interaction improves film microstructure. EOs change seaweed-based film microstructure. Thyme and lemongrass oils made the alginate-based film surface rougher **[73]**.

Different surface morphology (SEM) was found for films made with alginate and cinnamon essential oil compared to films made with only alginate. The rough texture and hollow structures seen in the EO-containing film may be attributed to the upward migration of oil droplets upon exposure to air **[74]**.

Properties of edible films fabricated with EOs and seaweed derivatives

Essential oils can be used to impart color to seaweed polysaccharide-based films, although the films are typically colorless. In addition to adding color, essential oils can reduce Maillard reactions and dehydration by inhibiting microorganism growth and oxidative stress **[75]**.

Seaweed-based films' physical and functional properties are crucial to their practical use. The mechanical properties, oxygen and water vapor barrier properties, hydrophobicity, and solubility in water are among the most important physical characteristics of an active food packaging film. Essential oils significantly impact these properties, and their effect on seaweed-based films will be briefly discussed in this article. An overview of seaweed-based packaging films by incorporating EOs is summarized in Table 4. Table 4 provides an overview of seaweed-based packaging films incorporating essential oils, including their composition, properties, and potential applications.

Table 4 Overview of seaweed-based packaging films by incorporating EOs.

Overview of seaweed-based packaging films by incorporating EOs			
Source	EOs used	production method	Reference
Agar	0.12% tea tree, 10.0% clove, 2.0% neem	solvent casting	**[37]**, **[76]**, **[77]**
Alginate	0.02% cinnamaldehyde , 3.0% clove	coating, solvent casting	**[78]**, **[79]**
Sodium alginate	2% ginger, 0.6% oregano, 1% lemongrass	coating, solvent casting	**[80]**, **[81]**, **[82]**
Carrageenan	10.0% zataria multiflora , 3.0% rosemary, 1% cinnamon	coating, solvent casting	**[83]**, **[84]**, **[85]**

Seaweeds can accumulate hazardous substances due to industrialization and the leakage of petroleum chemicals into the water, which can include arsenic, lead, and mercury despite their numerous benefits. The European Commission Regulation (EC) No. 629/2008 has set a maximum cadmium level of 3 mg/kg dry weight in edible seaweeds. The regulation also limits the quantity of arsenic in a full meal to 10-40 mg per kilogram of dry weight, while other toxic metals have no specific rules **[86]**.

The United States Food and Drug Administration (FDA) has published a list of essential oils that can be used as a food flavoring and classified them as Generally Recognized As Safe (GRAS), meaning they are safe to ingest if used in approved levels (US FDA 2018). Regulation (EC) No. 1334/2008 of the European Commission provides guidelines to ensure the safety of flavorings, and a revised and updated list of permitted flavors was published in an annex to the regulation on October 1, 2012. Only ingredients on the Union-approved list, which is included in Regulation (EC) No. 1334/2008, may be added to food **[87]**, **[88]**.

Essential oils (EOs) can be safely used as ingredients in food at recommended levels, but higher levels can cause allergic reactions **[89]**. Essential oils (EOs) can be safely used as ingredients in food at recommended levels, but higher levels can cause allergic reactions **[90]**. Some health problems, such as eye, skin, and mucous membrane irritations and sensitivity to EOs containing aldehydes or phenols, have been linked to essential oils **[91]**. A previous study has suggested that clove essential oil may lower blood glucose, acidosis, and ketonuria, among other effects **[92]**. Therefore, the value and potential side effects of EOs should be assessed before using them in food. Applications of Seaweed-Based Films in Food Packaging Current and potential applications of seaweed-based films in food packaging Advantages and challenges of using seaweed-based films in food packaging Comparison with other sustainable packaging options **[93]**.

Applications of Seaweed-Based Films in Food Packaging

Fresh Produce Packaging: Shelf-life extension of fruits and vegetables: Seaweed-based films have shown great potential in extending the shelf life of fruits and vegetables. These films act as a barrier, preventing the exchange of gases and moisture between the packaged produce and the surrounding environment. By creating a modifJied atmosphere within the packaging, the respiration rate of the fruits and vegetables can be slowed down, effectively delaying the onset of spoilage **[2]**.

The barrier properties of seaweed-based films help to reduce water loss from the produce, minimizing shrinkage and maintaining turgidity. This can significantly extend the shelf life of perishable fruits and vegetables, allowing them to remain fresh and appealing for a longer duration. By preventing moisture loss, the films also help to retain the natural juiciness of the produce, enhancing their sensory quality **[4]**.

Preservation of texture and nutritional quality

One of the key challenges in fresh produce packaging is maintaining the desired texture and nutritional quality of the fruits and vegetables. Seaweed-based films provide an excellent solution to address these concerns. These films create a microenvironment that helps to preserve the texture and structural integrity of the produce, preventing softening, wilting, or browning **[93]**.

Furthermore, seaweed-based films have been found to preserve the nutritional quality of fruits and vegetables. They can act as a protective barrier against light, which reduces the degradation of light-sensitive nutrients such as vitamins and antioxidants. This ensures that the packaged produce retains its nutritional value and remains a healthy choice for consumers.

Seaweed-based films also offer a unique advantage in terms of their bioactive compounds. Seaweeds are rich in bioactive components, such as polyphenols, polysaccharides, and antioxidants, which have been associated with various health benefits. These compounds can potentially migrate from the seaweed-based films to the packaged produce, providing additional health-enhancing properties **[4]**.

In summary, seaweed-based films play a vital role in fresh produce packaging by extending the shelf life of fruits and vegetables and preserving their texture and nutritional quality. These films act as effective barriers, creating a modified atmosphere that slows down the respiration rate and minimizes moisture loss. By utilizing seaweed-based films, the freshness, sensory appeal, and nutritional value of packaged produce can be significantly enhanced, reducing food waste and improving consumer satisfaction **[4]**.

Meat and Seafood Packaging

Preservation and quality maintenance: Seaweed-based films have proven effective in preserving and maintaining quality for meat and seafood products. These films act as a protective barrier, preventing the entry of oxygen and moisture, which are major contributors to the degradation of meat and seafood.

By creating a modified atmosphere within the packaging, seaweed-based films help to inhibit the growth of spoilage-causing microorganisms and reduce oxidative reactions, thus extending the shelf life of the products.

The barrier properties of these films also minimize the loss of natural juices and flavors, helping to maintain the sensory attributes and overall quality of the packaged meat and seafood **[92]**.

Furthermore, seaweed-based films exhibit antimicrobial properties due to the presence of bioactive compounds in seaweeds. These compounds can inhibit the growth of pathogenic bacteria, reducing the risk of foodborne illnesses and enhancing the safety of the packaged meat and seafood **[94]**.

Extended shelf life for meat and seafood products

Seaweed-based films offer the advantage of significantly extending the shelf life of meat and seafood products. The barrier properties of these films help to prevent moisture loss and protect against external contamination, thereby maintaining the freshness and integrity of the packaged products.

In the case of meat, the use of seaweed-based films can prevent dehydration and the subsequent loss of weight, preserving the juiciness and tenderness of the meat. It also helps to minimize the growth of spoilage bacteria and delay the onset of microbial spoilage, leading to an extended shelf life **[95]**.

For seafood, which is highly perishable, seaweed-based films play a crucial role in maintaining its quality and extending its shelf life. The films act as a barrier to prevent the entry of oxygen, which can cause oxidation and deterioration of the seafood. This helps to preserve the flavor, texture, and color of the packaged seafood, making it more appealing to consumers and reducing the potential for waste **[2]**.

By utilizing seaweed-based films in meat and seafood packaging, the industry can benefit from increased product shelf life, reduced food waste, and improved overall quality and safety of the packaged products. These films provide a sustainable and effective solution to preserve the freshness and extend the availability of meat and seafood, ensuring that they reach consumers in optimal condition **[92]**.

Bakery and Confectionery Packaging

Preservation of texture and freshness in baked goods: Seaweed-based films offer valuable benefits in the packaging of bakery and confectionery products, specifically in preserving their texture and freshness. These films act as a protective barrier, preventing the exchange of moisture and gases between the packaged products and the surrounding environment.

Moisture is a critical factor in maintaining the desired texture of bakery items. Seaweed-based films help to regulate the moisture content by reducing moisture loss from the products and minimizing the absorption of moisture from the environment. This helps to prevent staleness, hardness, or dryness in baked goods, ensuring that they retain their softness, moistness, and overall appealing texture **[4]**.

Furthermore, seaweed-based films contribute to the retention of freshness in baked goods. These films create a microenvironment within the packaging that helps to slow down the staling process. They can prevent moisture migration between different components of the baked goods, such as the crust and the crumb, which helps maintain their distinct textures and flavors over time **[92]**.

Prevention of staleness and shelf stability

Seaweed-based films play a crucial role in preventing staleness and enhancing the shelf stability of bakery and confectionery products. Staleness is primarily caused by the absorption of moisture from the surrounding environment, resulting in changes in texture, taste, and overall quality.

Seaweed-based films act as a moisture barrier, effectively preventing the transfer of moisture into the packaged products. By minimizing moisture uptake, these films help to maintain the crispness, flakiness, and overall freshness of bakery items, such as cookies, pastries, and bread **[96]**.

Moreover, seaweed-based films contribute to the shelf stability of bakery and confectionery products by protecting them from external factors that can accelerate deterioration. These films act as a barrier against light, which can lead to the degradation of light-sensitive ingredients such as fats, colors, and flavors. By reducing exposure to light, seaweed-based films help preserve the packaged products' visual appeal, taste, and aroma **[97]**.

In summary, seaweed-based films offer significant advantages in the packaging of bakery and confectionery items. They preserve the texture and freshness of baked goods, preventing staleness and maintaining their appealing attributes. These films also contribute to shelf stability by acting as a moisture and light barrier, ensuring that the products remain fresh, flavorful, and visually appealing for a longer duration **[92]**.

Ready-to-Eat Meals Packaging

Convenience and freshness for ready-to-eat meals Seaweed-based films provide several advantages in the packaging of ready-to-eat meals, offering convenience and ensuring the freshness of the packaged food. These films are highly versatile and can be tailored to accommodate different types of ready-to-eat meals, including pre-packaged salads, sandwiches, and complete meal kits.

Seaweed-based films offer a lightweight and flexible packaging solution, making them suitable for on-the-go consumption. The films are easy to handle and open, providing convenience for consumers who seek quick and hassle-free meal options. Additionally, these films can be designed with resealable features, allowing for multiple servings and maintaining the freshness of the remaining portions.

Furthermore, seaweed-based films help to preserve the freshness and quality of ready-to-eat meals. The films act as a barrier against moisture, preventing the loss of moisture from the food and the absorption of excess moisture from the environment. This helps to retain the desired texture, crispness, and juiciness of the packaged meals, ensuring an enjoyable eating experience for consumers.

Tamper-evident packaging for safety and integrity

Seaweed-based films offer tamper-evident packaging solutions for ready-to-eat meals, ensuring the safety and integrity of the packaged food. These films can be designed with features such as heat-sealed edges, tear strips, or tamper-evident labels that provide visible indicators of any tampering or unauthorized access to the package.

The tamper-evident properties of seaweed-based films are particularly important in ensuring food safety and building consumer trust. They offer protection against contamination and unauthorized opening of the packaged meals, reducing the risk of foodborne illnesses and maintaining the integrity of the food. The clear visibility of tampering indicators helps consumers make informed decisions about the safety and suitability of the product.

Seaweed-based films also contribute to sustainable packaging practices in the ready-to-eat meal sector. By utilizing renewable and biodegradable seaweed-based materials, these films offer an environmentally friendly alternative to traditional single-use plastics, reducing the overall environmental impact.

In conclusion, seaweed-based films provide convenient and fresh packaging solutions for ready-to-eat meals. They offer convenience to consumers on the go and help preserve the freshness and quality of the packaged food. Moreover, these films offer tamper-evident packaging features, ensuring the safety and integrity of the ready-to-eat meals. The utilization of seaweed-based films in this context aligns with sustainable packaging practices, contributing to a more environmentally friendly approach to food packaging.

Beverage Packaging

Single-serve sachets for liquid beverages: Seaweed-based films offer a practical solution for the packaging of liquid beverages, particularly in the form of single-serve sachets. These films provide a lightweight and flexible packaging option that is ideal for individual portions of beverages, such as energy drinks, juice concentrates, or instant coffee.

The use of seaweed-based films in single-serve sachets provides convenience for consumers. The films are easily tearable, allowing for effortless opening and pouring of the beverage. This makes them suitable for on-the-go consumption, providing a quick and convenient way to enjoy a refreshing drink.

Additionally, seaweed-based films contribute to the preservation of the beverage's quality. These films act as a barrier against oxygen and light, which are known to degrade the flavor, color, and nutritional content of beverages. By reducing exposure to these detrimental factors, seaweed-based films help to maintain the sensory attributes and overall freshness of the packaged liquid beverages.

Portability and sustainability in on-the-go packaging

Seaweed-based films offer portability and sustainability benefits in the packaging of beverages for on-the-go consumption. The films are lightweight and flexible, making them easy to carry and handle. They can be conveniently folded or rolled, occupying minimal space in bags or pockets, making them an excellent choice for portable beverages.

Moreover, seaweed-based films align with sustainable packaging practices. They are derived from renewable and biodegradable seaweed sources, making them environmentally friendly alternatives to traditional single-use plastics. The use of seaweed-based films helps to reduce the dependence on fossil fuel-based packaging materials, contributing to the overall reduction of plastic waste and environmental impact.

In summary, seaweed-based films offer practical and sustainable packaging solutions for beverages. Single-serve sachets made from these films provide convenience and ease of use for individual portions of liquid beverages. The portability and lightweight nature of seaweed-based films make them suitable for on-the-go consumption. Additionally, their sustainability benefits contribute to reducing plastic waste and promoting environmentally friendly packaging practices in the beverage industry.

Dairy Product Packaging

Oxygen and moisture barrier for dairy products: Seaweed-based films offer excellent oxygen and moisture barrier properties, making them an ideal packaging solution for dairy products. These films create a protective barrier that helps to prevent the entry of oxygen and moisture into the packaged dairy items, ensuring their quality and freshness.

Oxygen is known to contribute to the deterioration of dairy products by promoting oxidation and spoilage. Seaweed-based films act as a barrier against oxygen, reducing the exposure of dairy products to this element. This helps to maintain the flavor, texture, and nutritional integrity of dairy items, such as milk, cream, and dairy-based beverages.

Additionally, moisture can negatively impact the quality of dairy products by causing microbial growth, spoilage, and textural changes. Seaweed-based films provide an effective moisture barrier, minimizing moisture transfer between the product and the environment. By controlling moisture levels, these films help to extend the shelf life of dairy products and preserve their desired characteristics.

Sustainable packaging solution for cheese, yogurt, and butter: Seaweed-based films offer a sustainable packaging solution for a range of dairy products, including cheese, yogurt, and butter. These films are derived from renewable and biodegradable seaweed sources, making them an environmentally friendly alternative to conventional plastic packaging materials.

Cheese packaging can benefit from seaweed-based films due to their moisture regulation properties. These films help to maintain the proper moisture balance in the cheese, preventing drying out or excessive moisture absorption. This ensures that the cheese retains its texture, flavor, and overall quality during storage and transportation.

For yogurt packaging, seaweed-based films contribute to the preservation of freshness and consistency. These films provide an effective barrier against oxygen and moisture, preventing the growth of spoilage microorganisms and maintaining the smooth texture and taste of the yogurt. The sustainable nature of seaweed-based films aligns with the growing consumer demand for eco-friendly packaging options for dairy products.

Butter packaging can also benefit from seaweed-based films due to their ability to create a protective barrier against oxygen and moisture. These films help preserve butter's flavor, aroma, and texture, ensuring its quality and extending its shelf life. The use of sustainable seaweed-based films in butter packaging reflects a commitment to environmentally conscious practices in the dairy industry.

Future Directions and Conclusion

Improving the mechanical properties of seaweed-based films is crucial to ensure their suitability for food packaging and transportation. Further research and development efforts are needed to enhance their mechanical strength and durability. Scientists and engineers can explore innovative techniques, such as modifying the film's composition or processing conditions, to enhance its structural integrity and resistance to tearing or puncture. By improving these mechanical properties, seaweed-based films can effectively protect food products during storage, handling, and distribution.

Extending the shelf life of seaweed-based films is another important area of focus. Researchers can investigate methods to enhance the film's stability and usability over extended periods. This involves studying the factors that contribute to film degradation, such as moisture absorption or oxidation, and developing strategies to mitigate their effects. By understanding the degradation mechanisms and implementing appropriate protective measures, the shelf life of seaweed-based films can be prolonged, ensuring their functionality and quality throughout the entire food supply chain.

To meet the increasing demand for seaweed-based films, there is a need to scale up their production. Developing efficient and sustainable methods for large-scale cultivation and processing of seaweed is essential. This may involve optimizing cultivation techniques, exploring different seaweed species with desirable properties, and implementing advanced processing technologies. By increasing production capacity and streamlining the supply chain, the availability of seaweed-based films can be expanded, making them more accessible to the food packaging industry.

Cost reduction is a significant factor for the widespread adoption of seaweed-based films. Exploring cost-effective approaches in the production and processing of these films is essential to enhance their economic competitiveness compared to traditional packaging materials. This can involve optimizing production processes, utilizing locally available resources, and leveraging economies of scale. By finding ways to reduce production costs without compromising the film's quality and performance, seaweed-based films can become a financially viable and attractive option for food packaging applications.

Innovation in formulation is a key aspect of advancing seaweed-based films for food packaging. Researchers can experiment with composite materials and novel formulations to optimize the functional properties of these films. The barrier properties, mechanical strength, and other desirable characteristics of seaweed-based films can be further enhanced by incorporating additives or modifiers, such as natural polymers or nanoparticles. Tailoring the formulation of these films for specific food packaging applications can lead to improved performance and wider versatility in the industry.

In conclusion, addressing the challenges related to the mechanical properties, shelf life extension, scaling up production, cost reduction, and formulation innovation is essential for the future development and widespread adoption of seaweed-based films in food packaging. By dedicating research efforts to these areas, we can unlock the full potential of seaweed-based films as sustainable and high-performing packaging materials, contributing to a more environmentally friendly and efficient food supply chain.Conclusion and Summary of Key Points Seaweed-based films present a promising solution for sustainable food packaging, addressing the need for environmentally friendly alternatives to conventional plastics. Their renewable sourcing, biodegradability, good barrier properties, and consumer acceptance make them attractive for various food packaging applications. Although challenges such as scalability, cost, mechanical strength, and shelf life need to be overcome, ongoing research and development efforts are driving the advancement of seaweed-based films. By further improving their properties and optimizing production processes, seaweed-based films have the potential to become a widely adopted and environmentally conscious packaging option, contributing to a more sustainable and circular economy.

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