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Macroalgae-Based Bio-Based Packaging: Characteristics, Green Extraction Methods, and Applications as Sustainable Solutions

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***Abstract*—Macroalgae represents a sustainable and environmentally friendly resource for developing bio-based packaging materials to prolong the shelf life of fruits and vegetables. This review explores the unique properties of red, brown, and green algae, rich in bioactive compounds that offer significant advantages as bio-based packaging materials. The review highlights green extraction methods such as supercritical fluid extraction, enzymatic-assisted extraction, microwave-assisted extraction, and ultrasound-assisted extraction, which optimize the yield of the bioactive compounds. These methods are advantageous over conventional techniques due to their low solvent usage, high selectivity, rapid processing, and reduced extract degradation. Additionally, the review delves into macroalgae's antioxidant and antimicrobial properties and their impact on enhancing the shelf life of perishable produce. Regulatory aspects concerning incorporating macroalgae compounds into food packaging materials are examined alongside consumer perceptions and acceptance of these innovative packaging solutions. The widespread consumption of macroalgae in ASEAN countries underscores its safety and familiarity, paving the way for broader acceptance of macroalgae-based packaging in global markets. In summary, utilizing macroalgae in bio-based packaging presents a sustainable solution to food preservation. It leverages the bioactive properties of algae to extend the shelf life of fruits and vegetables. This review underscores the potential of macroalgae as a viable alternative to conventional packaging materials, aligning with global sustainability goals and consumer preferences for eco-friendly products.**

***Keywords*—Macroalgae; food packaging; green extraction; shelf life; sustainability.**

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I. INTRODUCTION

The development of innovative packaging materials utilizing biodegradable and compostable polymers as alternatives to traditional, long-lasting polymers garner significant attention across multiple sectors, including the plastics industry and broader societal contexts. The promotion of sustainable packaging practices is well-documented in both academic and industry literature, emphasizing the principles of the circular economy, recyclability, and natural aesthetics [1], [2], [3], [4], [5]. Packaging plays a crucial role in food processing by providing essential functions such as protection, containment, and information dissemination [6]. The scale of plastic production is staggering; from 1950 to 2017, global production reached 9.2 billion tons, with projections estimating a cumulative output of 34 billion tons by 2050. This rise correlates to approximately 300 million tons of annual plastic waste [7]. According to Wu et al. [8], the sector's value is projected to reach 320.94 billion USD within the next five years, maintaining an annual growth rate of 4.0%. The packaging industry generates higher waste rates compared to other sectors. In response to this environmental challenge, the European Commission has implemented policies to foster a transition towards a circular economy model, promoting sustainability and waste reduction [9]. These policies are crucial for mitigating the environmental impact of packaging waste and supporting the development of more sustainable materials and practices within industry.

The extensive use of petroleum-based plastics has led to the depletion of non-renewable resources and has significantly exacerbated environmental challenges, raising considerable sustainability concerns [10], [11]. Various strategies have been proposed to mitigate packaging waste in response to these challenges. A primary strategy involves adopting biodegradable materials as alternatives to traditional non-biodegradable plastics, which do not decompose after use. This approach is particularly emphasized within the food industry to enhance recycling efforts [12], [13], [14]. As defined by the ASTM D7075-04 standard, bio-based packaging materials are derived from carbon-based compounds sourced from biological origins rather than fossil fuels. These materials offer notable environmental benefits, including a reduced carbon footprint and enhanced biodegradability, making them particularly suitable for food applications [15]. The shift to bio-based packaging addresses the critical issue of plastic waste. It supports a more sustainable and circular economy by reducing dependency on fossil resources and lowering greenhouse gas emissions. This transition is essential for achieving long-term sustainability goals and minimizing the environmental impact of packaging waste.

Recent advancements in food packaging technologies have emphasized using biomass leftovers as the primary raw materials for producing bio-based packaging products. This innovation reflects a growing global demand for sustainable packaging solutions, with an estimated capacity of approximately 7.85 million tons as of 2019 [16], [17], [18], [19]. These developments address the pressing issue of plastic waste and promote a circular economy by utilizing renewable resources and enhancing the sustainability of packaging practices. Currently, the food packaging industry currently relies heavily on non-biodegradable petroleum-based products, such as monomers, plasticizers, and oligomers, which pose potential food safety risks due to chemical migration during food processing [20]. Increasing environmental and consumer concerns have driven the development of biobased packaging materials. These materials, derived from renewable resources, aim to reduce carbon footprints, minimize environmental impacts from packaging waste, and improve consumer acceptance. Additionally, they strive to maintain the barrier properties and extend the shelf life of packaged goods [21], [22], [23]. The pursuit of sustainable food packaging alternatives includes the creation of compostable, reusable, and natural material-based solutions supported by advanced technologies [24], [25], [26].

In the quest to sustainably enhance the shelf life of food products, adopting macroalgae-based biobased packaging presents a compelling solution. Macroalgae, commonly known as seaweed, possesses key characteristics such as high stiffness, biocompatibility, low deformability, and biodegradability, which meet the increasing demand for eco-friendly and rapidly compostable packaging solutions [27]. Unlike terrestrial plants, seaweed exhibit rapid growth without requiring arable land, freshwater, or fertilizers, representing a highly sustainable resource [28]. Polysaccharides extracted from seaweed, including alginic acid, fucoidan, and cellulose, are notably processable and degradable. These attributes make them suitable for developing biobased materials that can effectively substitute conventional petroleum-based plastics [29], [30]. The global food industry is confronted with the dual challenges of reducing food waste and minimizing the environmental impacts of packaging materials, highlighting the significance of a circular economy approach [31], [32]. Within this framework, seaweed biomass emerges as a promising candidate for producing entirely biodegradable packaging materials, offering a viable pathway to mitigate environmental degradation and promote sustainability in food packaging [33]. This approach supports environmental conservation and aligns with global sustainability goals by leveraging renewable resources to address critical challenges in food preservation and waste reduction.

Despite their widespread use, conventional petroleum-based plastics significantly contribute to environmental degradation and pose long-term sustainability concerns. Addressing plastic pollution through technological advancements alone proves insufficient [34]. However, leveraging macroalgae extract for sustainable biobased packaging presents a promising alternative. Macroalgae can be easily cultivated in natural environments, adapt to diverse conditions, and be harvested year-round. They also yield high biomass rich in protein, are non-toxic, and environmentally friendly, making them an ideal resource for sustainable packaging solutions [35]. The extensive availability of macroalgae in oceans and coastal regions highlights its potential across various sectors. In addition to its application in sustainable packaging, macroalgae can be utilized in high-quality food production, animal feed, pharmaceuticals, cosmetics, fertilizers, and biomaterials. It is also instrumental in the production of phycocolloids such as agar and carrageenan, which have significant industrial applications [36], [37], [38], [39], [40]. Integrating macroalgae into these diverse fields can significantly reduce our reliance on petroleum-based plastics, thereby mitigating environmental impact and promoting sustainability. This multifaceted approach addresses plastic pollution and enhances macroalgae's economic and ecological value.

II. MATERIALS AND METHOD

A. Macroalgae

Macroalgae, commonly called seaweed, represent one of the world's most extensive untapped, low-trophic, renewable biomass resources. As of 2018, global seaweed production reached 32.4 million tons, with aquaculture contributing 97%. According to FAO's State of World Fisheries and Aquaculture reports for 2016 and 2020, the seaweed market was projected to reach a valuation of 13.3 billion USD. There are over 10,000 known seaweed species globally, and approximately 300 are commercially exploited in more than 50 countries. The composition of commercially utilized species includes 46% brown algae, 54% red algae, and less than 1% green algae [41]. The potential of macroalgae as a renewable biomass resource is significant due to its extensive diversity and substantial global production. Seaweed aquaculture has emerged as a critical sector, driving most of the production and offering a sustainable alternative to land-based biomass resources. The economic valuation highlights the substantial market opportunities within the seaweed industry, further underscoring its commercial viability [42]. The diverse applications of seaweed, spanning food, pharmaceuticals, cosmetics, and biofuels, position it as a versatile and valuable resource. Given the current trends and the projected market growth, the seaweed industry is poised to play a pivotal role in the global economy and sustainable resource management.

Asian countries dominate global seaweed production, notably China, Indonesia, South Korea, the Philippines, North Korea, and Japan [43]. Most of the seaweed production (87%) is allocated for direct human consumption, either fresh or dried as staple foods (85%) or further processed into food additives (15%), such as hydrocolloids like alginate, agar, and carrageenan [44]. The increasing interest in seaweed stems from its significant potential to contribute to a sustainable and nutritious global food supply, which is crucial for supporting a projected 70% increase in the global population by 2050.

Seaweed extracts contain a diverse array of beneficial compounds, including macro and micronutrients, proteins, polysaccharides, phenolic compounds, phytohormones, and osmolytes [45], [46]. They are categorized into macroalgae and microalgae, with macroalgae being visible to the naked eye and microalgae requiring microscopic observation (e.g., Scenedesmus, Chlorophyta). Macroalgae are further classified by color into brown seaweed (Phaeophyta), red seaweed (Rhodophyta), and green seaweed (Chlorophyta) [47], [48]. The structural complexity of macroalgae influences the variety and abundance of epifaunal communities associated with them [49].

Red seaweed (Rhodophyta) extracts have been extensively studied for their potential use in edible coatings due to their abundant biopolymers, primarily sulfated galactan like agar and carrageenan [50], [51]. When applied as coatings on food surfaces, these natural polymers contribute to enhanced antioxidant activity, antibacterial properties, and moisture barrier capabilities. The polysaccharides derived from red seaweed, including agar, agarose, and carrageenans, are characterized by α-1,3 and β-1,4 glycosidic linkages between alternate units of d-galactose and 3,6-anhydrogalactose [52], [53]. The film-forming properties of these galactans make them suitable for creating thin, protective coatings that improve food preservation and appeal by reducing water evaporation and inhibiting microbial growth.

Similarly, brown algae (Phaeophyta) are rich in polysaccharides such as alginate, agar, and carrageenan, making them suitable for producing biopolymer films with applications in biodegradable food packaging [54], [55], [56], [57]. Alginate, the most abundant polysaccharide in brown seaweed, contributes significantly to the development of oxygen-proof, edible films that prevent microbial contamination and preserve product quality during transportation [58]. Together with other seaweed phycocolloids, alginate serves as an excellent material for developing biodegradable films suitable for preserving fruits and other perishable foods. The composition of these materials typically includes minor monosaccharides such as xylose, galactose, arabinose, and rhamnose, alongside the predominant sugar, fucose, which forms the backbone of these polysaccharides [59]. Laminarin, a specific storage glucan found in seaweed, consists of glucose residues linked by β-1,3- and branching β-1,6-bonds [60]. In brown seaweed, alginate emerges as the predominant polysaccharide and biomolecule, widely recognized for its abundance and versatility [61]. Alginate, primarily sourced from brown seaweeds, finds extensive application in various industries, notably in the production of biodegradable food packaging [62]. Recent advancements have also explored the use of alginate in 3D printing applications, including bioprinting scaffolds for tissue regeneration [63].

B. Agar

Agar, a complex polysaccharide predominantly derived from galactose, serves as an essential structural component within the cell walls of various species belonging to the Rhodophyceae (red algae) family. This polysaccharide consists of two principal components: agarose and agaropectin. Agarose constitutes the gelatinous fraction of agar and comprises repeating units known as agarobiose. These units are characterized by alternating β-D-galactopyranosyl and 3,6-anhydro-α-L-galactopyranosyl groups, which contribute to its unique properties [64]. Agaropectin, on the other hand, represents the non-gelling portion of agar. Although it is structurally similar to agarose, agaropectin incorporates additional components such as 5-10% sulfate esters, methoxyl groups, pyruvic acid residues, and polysaccharide chains. The 3,6-anhydro-α-L-galactose units may be substituted in these chains by α-L-galactose 6-sulfate units [65]. The physical properties of agar are significantly influenced by the type, quantity, and positioning of these substituents [66].

When the agar is dissolved in hot water under specific conditions, it forms a slightly viscous solution that undergoes thermos-reversible gelation upon cooling. The gelation characteristics of agar are primarily determined by the distribution and amount of sulfate groups, in addition to the content of the 3,6-anhydrogalactose fraction within the phycocolloid. Due to its moderate degree of sulphation, agar exhibits a high gelling capacity, which facilitates the formation of a robust gel network without excessive aggregation. This characteristic ensures the strength and flexibility of the gel [67]. Agar's versatility extends beyond its traditional uses in the food industry as a texture modifier and thickener. Current research initiatives are exploring its potential in various innovative applications. For instance, agar is being investigated for the development of biodegradable films, which could offer environmentally friendly alternatives to conventional plastics [68], [69]. Moreover, agar-based hybrid biopolymeric nanofibers are being designed for use in advanced biomedical and industrial applications [70].

Another promising area of research involves the use of agar in encapsulation structures. These structures can protect and deliver bioactive compounds, enhancing their stability and efficacy [71]. Additionally, agar is being studied for its functional components that exhibit bioactive properties, including antioxidant and anticancer activities. These properties highlight agar's potential as a multifunctional material with significant health benefits [72]. The exploration of agar's applications in biodegradable films involves the synthesis of films with desirable mechanical and barrier properties. These films are biodegradable, making them suitable for packaging applications where environmental sustainability is a priority. Researchers are focusing on optimizing the film-forming conditions and incorporating various additives to enhance the performance of agar-based films. For example, incorporating plasticizers can improve the flexibility and durability of these films, making them more practical for commercial use.

In the realm of hybrid biopolymeric nanofibers, agar is being combined with other biopolymers to create nanofibers with enhanced properties. These nanofibers are produced using electrospinning techniques, which allow for precise control over the fiber diameter and morphology. The resulting nanofibers exhibit improved mechanical strength, biocompatibility, and functionality, making them suitable for applications such as wound dressings, drug delivery systems, and tissue engineering scaffolds. Encapsulation structures utilizing agar are being developed to protect sensitive bioactive compounds from degradation and enhance their controlled release. These structures can be used in various fields, including pharmaceuticals, nutraceuticals, and cosmetics. The encapsulation process involves the formation of gel matrices that encapsulate the bioactive compounds, providing a protective barrier and allowing for sustained release over time. This approach improves the stability and bioavailability of the encapsulated compounds, maximizing their therapeutic potential. Furthermore, the bioactive properties of agar are being extensively studied to harness its health benefits. Agar contains natural antioxidants, which can neutralize harmful free radicals and protect cells from oxidative damage. These antioxidants contribute to the prevention of chronic diseases such as cardiovascular diseases, neurodegenerative disorders, and cancer. Additionally, agar exhibits anticancer activities by inhibiting the growth and proliferation of cancer cells. Researchers are investigating the mechanisms underlying these bioactive properties and exploring the potential of agar-derived compounds as therapeutic agents.

C. Carrageenan

Carrageenan is sulfated linear galactans predominantly found in the cell walls of red algae (Rhodophyta), where they play a crucial role in densely packing the cellulose microfibril network. These polysaccharides can constitute up to 50% of the dry weight of the algae, indicating their significant presence and importance [73]. The molecular weight of carrageenan varies widely, with a weight-average molecular weight distribution ranging from 30 kDa to 5000 kDa, illustrating the diversity in their structural complexity. Structurally, carrageenan is composed of repeating disaccharide units, referred to as carrabioses, which consist of d-galactose (G) linked alternately by α-1,3 and β-1,4 glycosidic linkages [74]. Based on the number and position of ester sulfate groups and the presence of 3,6-anhydrogalactose residues, carrageenan are classified into three main types: kappa (κ), iota (ι), and lambda (λ). Each type exhibits unique properties that determine its specific applications. For instance, higher levels of ester sulfate groups generally result in a lower solubility temperature and greater gel strength, which are critical for various industrial applications.

Kappa-carrageenan (κ-carrageenan) features a linear structure composed of alternating disaccharide units of 1,3-linked β-D-galactose-4-sulfate and 1,4-linked 3,6-anhydro-α-D-galactose. This specific arrangement imparts distinct gelling properties suitable for various applications. In contrast, iota-carrageenan (ι-carrageenan) incorporates an additional sulfated group at the C-2 position of the 1,4-linked galactose unit, modifying its gelation and solubility characteristics. Lambda-carrageenan (λ-carrageenan) includes a third sulfated group at the C-6 position of the 1,4-linked galactose unit, which significantly influences its non-gelling behavior. One of the primary sources of carrageenan production globally is the red seaweed *Kappaphycus alvarezii*, which contributes to over 80% of the total carrageenan production [75]. Beyond *Kappaphycus alvarezii*, carrageenan has also been isolated from various other red seaweeds such as Chondrus crispus (commonly known as Irish moss), *Ahnfeltiopsis devoniensis*, and *Sarcodiotheca gaudichaudi*i [76], [77], [78], [79]. This broad range of sources underscores the versatility and widespread availability of carrageenan in marine environments.

Carrageenan's unique properties make it highly valuable in various applications. In the food industry, it is extensively used in edible coatings because it acts as a moisture and gas barrier, prevents food discoloration, and enhances texture [79]. These properties are particularly beneficial for preserving the quality and extending the shelf life of food products. Additionally, carrageenan serves as a stabilizer, emulsifier, and thickening agent, finding widespread use in food and the cosmetic and pharmaceutical industries. Its functional properties are exploited to improve product stability, texture, and consistency. Beyond these conventional applications, carrageenan also has emerging uses as a biostimulant and immunostimulant [80], [81]. It can enhance plant growth and resilience as a biostimulant, contributing to sustainable agricultural practices. Its immunostimulant properties are being explored for potential benefits in promoting health and preventing diseases.

The utilization of seaweed-derived biopolymers, such as carrageenan, in biopolymer film production is particularly noteworthy. These biopolymers offer high-quality and durable materials while addressing environmental concerns associated with synthetic polymers. Carrageenan's hydrophilic nature and the presence of negatively charged sulfate groups along the polymer chain enable it to bind water and hydroxyl groups effectively. This characteristic contributes significantly to its stabilizing and film-forming capabilities, making it an ideal candidate for developing sustainable biopolymer films [82]. Thus, carrageenan is an integral component of red algae, playing a critical role in the structure and function of their cell walls. Their diverse molecular weight and structural variations enable a wide range of applications across different industries. From food preservation and enhancement to cosmetic and pharmaceutical applications, carrageenan's multifunctional properties make it a versatile and valuable biopolymer. Additionally, its potential as a biostimulant and immunostimulant opens new avenues for sustainable agricultural practices and health benefits. The development of carrageenan-based biopolymer films further exemplifies its role in advancing environmentally friendly materials, highlighting its significance in addressing contemporary environmental challenges.

D. Alginate

Alginate, an anionic polysaccharide predominantly derived from brown seaweeds (Phaeophyta), plays a significant role in the food industry due to its stabilizing, emulsifying, gelling, and thickening properties [83], [84]. Key sources of alginate include major brown algae species such as Macrocystis, Laminaria, Ascophyllum, Ecklonia, Eisenia, Nereocystis, and Sargassum. Structurally, alginates are composed of β-D-mannuronic acid (M alginate) and α-L-guluronic acid (G alginate) monomers, connected by 1,4 glycosidic bonds. The high content of guluronic acid within alginates imparts gel-forming properties, which are advantageous for a range of culinary applications [85], [86], [87]. A pivotal attribute of alginate is its ability to selectively bind multivalent cations, which is essential for its gel formation capabilities [88]. Among these cations, alkaline earth metals display varying affinities for alginate, with calcium ions (Ca^{2+}) exhibiting stronger binding compared to strontium (Sr^{2+}) and barium (Ba^{2+}) ions. In contrast, monovalent cations and magnesium ions (Mg^{2+}) generally do not facilitate gel formation with alginate. Although divalent cations such as lead (Pb^{2+}), copper (Cu^{2+}), cadmium (Cd^{2+}), cobalt (Co^{2+}), nickel (Ni^{2+}), zinc (Zn^{2+}), and manganese (Mn^{2+}) can form gels with alginate, their toxicological implications preclude their use in food applications, emphasizing the necessity of employing safe and food-grade materials [89].

In practical applications, sodium alginate forms thick and stable gels in solutions through the crosslinking of the carboxylate ions of alginate guluronate units with calcium ions [90]. This property is particularly exploited in the development of edible coatings and films for the food industry. Initially, alginate films exhibit poor moisture barrier properties; however, the incorporation of calcium ions significantly enhances their ability to resist moisture permeation, thus improving food preservation [91]. Within the context of food packaging, polysaccharides derived from macroalgae—such as alginate, agar, and carrageenan—are of paramount importance due to their natural origin and beneficial properties. Alginate, primarily sourced from brown algae, functions effectively in food packaging by acting as a sacrificial moisture absorber, thereby preserving the natural moisture content of food products. These polysaccharide-based coatings and films regulate gas exchange, such as oxygen and carbon dioxide, extending the shelf life of perishable items and enhancing their visual appeal. Similar functionalities are observed with agar and carrageenan, derived from specific red seaweed varieties, further underscoring their utility as sustainable alternatives in contemporary food packaging applications.

Alginates are complex carbohydrates comprising repeating units of β-D-mannuronic acid and α-L-guluronic acid. The ratio and sequence of these monomers determine the physical properties of the alginate, including its gel strength and elasticity. High guluronic acid content is associated with stronger, more rigid gels, which are particularly useful in the food industry for creating firm textures in products such as jellies, custards, and restructured foods [87]. The gelation process of alginate is highly dependent on the presence of divalent cations, particularly calcium ions. When alginate meets calcium ions, a three-dimensional network is formed, creating a gel matrix that can encapsulate and stabilize various food components. This characteristic is exploited in the production of edible films and coatings, which serve as barriers to moisture and gas, thereby extending the shelf life of food products [90]. The formation of these films involves the application of an alginate solution to the food surface, followed by a treatment with calcium chloride to induce gelation.

The role of alginate in food packaging extends beyond its gelling properties. Alginate-based films can be engineered to possess specific permeability characteristics, allowing for controlled release of active ingredients, such as antimicrobials or antioxidants, which can further enhance food preservation. Additionally, the biodegradability of alginate makes it an environmentally friendly option compared to traditional plastic packaging, aligning with the increasing demand for sustainable packaging solutions. Agar and carrageenan, like alginate, are polysaccharides derived from seaweed, but they come from different classes of algae. Agar is derived from red algae in the Gelidiaceae and Gracilariaceae families, whereas carrageenan comes from red algae in the Gigartinaceae family. These polysaccharides share similar gelling properties with alginate but have distinct differences in their chemical structures and gelling mechanisms. Agar forms gels through hydrogen bonding, which are thermally reversible, meaning they can melt upon heating and re-solidify upon cooling. This property makes agar particularly useful in applications where temperature control is critical, such as in microbiological media and certain confectionery products. Carrageenan, on the other hand, forms gels through the interaction with potassium or calcium ions, depending on the type of carrageenan (kappa, iota, or lambda). Kappa-carrageenan forms strong, rigid gels with potassium ions, while iota-carrageenan forms elastic gels with calcium ions. Lambda-carrageenan does not gel but is used for thickening properties [85].

The functional similarities between these polysaccharides make them valuable in food technology, yet their unique properties allow for their use in diverse applications. For instance, agar is commonly used in the production of clear gels, which are desirable in desserts and microbiological culture media. Carrageenan is frequently used in dairy products to improve texture and stability, particularly in products like chocolate milk, ice cream, and cheese. The integration of alginate, agar, and carrageenan into food packaging systems leverages their natural, biodegradable nature, which is increasingly important in reducing the environmental impact of packaging waste. These polysaccharides not only improve the functional properties of food products but also contribute to the sustainability of the food industry by providing alternatives to synthetic polymers.

The utilization of alginate and other seaweed-derived polysaccharides in the food industry exemplifies the convergence of natural resources and technological innovation. The ability of alginate to form gels, stabilize emulsions, and function as a moisture barrier highlights its versatility and importance in food science. The incorporation of calcium ions enhances these properties, making alginate-based films and coatings highly effective in preserving food quality and extending shelf life. As the demand for sustainable and eco-friendly food packaging solutions grows, the role of natural polysaccharides like alginate, agar, and carrageenan will become increasingly significant. Their biodegradability, combined with their functional benefits, positions these materials as key components in developing next-generation food packaging systems.

III. RESULTS AND DISCUSSION

A. *Supercritical Fluid Extraction (SFE)*

Supercritical Fluid Extraction (SFE) is a sophisticated method for extracting chemical compounds from marine seaweed, distinguished by its efficiency in recovering bioactive substances from complex matrices [92]. The process relies on supercritical fluids (SFs), such as carbon dioxide (CO_2), which are maintained above their critical temperature and pressure, exhibiting properties that blend those of both gases and liquids. The concept of a critical point, introduced by Thomas Andrews in 1869, defines the conditions under which a substance can exist as both vapor and liquid in equilibrium [93].

In SFE, SFs like CO_2 possess unique solvent capabilities akin to liquids and transport properties like gasses due to their phase behavior above the critical point. This method surpasses conventional extraction techniques by minimizing solvent usage, ensuring high selectivity in extraction, facilitating rapid processing, and reducing degradation of the extracted compounds [94]. Moreover, the polarity of CO_2 can be adjusted by incorporating small quantities of co-solvents such as ethanol or methanol, thereby enhancing its efficacy in dissolving semi-polar and polar compounds. CO_2 is particularly favored in SFE applications within the food industry owing to its inert, non-toxic, non-flammable nature, and environmental compatibility [95]. Its thermodynamic properties and capacity to dissolve nonpolar and low-polarity compounds further underscore its suitability as an extraction solvent [96].

SFE typically involves several key steps. Firstly, the seaweed sample is placed in an extraction vessel where CO_2 is pressurized above its critical point (31.1°C and 73.8 atm). Under these conditions, CO_2 behaves like a dense gas with excellent penetration properties. As it permeates the seaweed matrix, CO_2 interacts with the bioactive compounds, dissolving them into the fluid phase. The dissolved compounds are then carried out of the extraction vessel into a separation chamber, where the pressure and temperature are adjusted to recover CO_2 and obtain the extracted substances. The control over pressure and temperature in SFE is crucial, as these parameters determine the solubility of different compounds and influence the efficiency of extraction.

One of the primary advantages of SFE is its ability to extract delicate compounds without damaging their chemical structure or functionality. This is particularly beneficial for bioactive compounds found in seaweed, such as polyphenols, polysaccharides, and essential oils, which may be susceptible to degradation under harsher extraction conditions. The high selectivity of CO_2 in SFE ensures that only the desired compounds are extracted, while unwanted contaminants or solvent residues are minimized, enhancing the purity and quality of the extracts obtained. Furthermore, the rapid processing times associated with SFE make it suitable for large-scale industrial applications. Compared to traditional solvent extraction methods, which may require prolonged extraction times and large volumes of organic solvents, SFE offers a more efficient and environmentally sustainable alternative. The use of CO_2 as a solvent also aligns with regulatory requirements for food and pharmaceutical applications, where safety and purity standards are stringent.

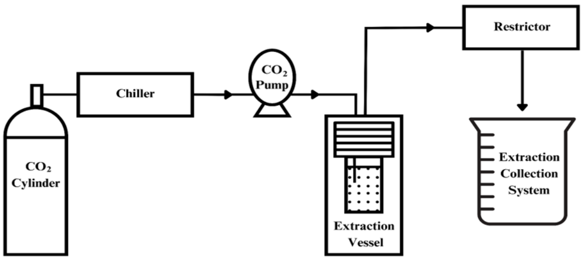

Fig. 1 Set-up for Supercritical Fluid Extraction

B. *Enzymatic Assisted Extraction (EAE)*

Enzymatic Assisted Extraction (EAE) utilizes the catalytic activity of enzymes to facilitate the breakdown of cellular structures, enabling the release of metabolites into the extraction solvent (Fig. 2) [97]. Typically, this solvent can be organic, or water based [98]. Enzymatic action enhances cellular disruption, allowing the solvent to penetrate more effectively and extract target compounds [99], [100]. This method is favored for its gentle processing conditions, which help preserve the integrity and bioactivity of sensitive compounds, resulting in higher extraction yields and efficiency [101]. The selection of appropriate enzymes is crucial at the outset of the extraction process. Enzymes are chosen based on their specificity towards components of cell walls or matrices. For instance, cellulase enzymes are effective in degrading cellulose, while proteases are employed to break down proteins [102]. This targeted enzymatic approach ensures selective extraction of desired metabolites while minimizing the extraction of unwanted components.

Enzymatic extraction offers several advantages over traditional methods. Firstly, it enhances selectivity by specifically targeting the desired compounds, thereby reducing the extraction of non-target substances. Secondly, it operates under milder conditions compared to mechanical or chemical methods, which can degrade heat-sensitive bioactive compounds. Thirdly, enzymatic processes are environmentally sustainable as they often require less energy and produce fewer harmful by-products. Moreover, they are considered safer for food and health applications due to their non-toxic nature and ability to produce cleaner extracts free from chemical residues [102]. The efficiency and efficacy of enzymatic extraction depend on several factors, including enzyme type and concentration, extraction conditions (pH, temperature), and the nature of the target material. Optimization of these parameters is critical to maximizing extraction efficiency and maintaining the quality of extracted metabolites.

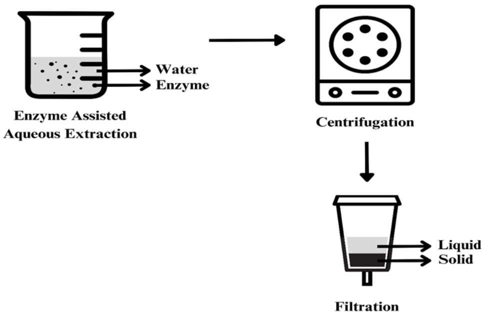

Fig. 2 Set-up for Enzyme Assisted Extraction

C. Microwave Assisted Extraction (MAE)

Microwave Assisted Extraction (MAE) represents an innovative and environmentally friendly approach for extracting biologically active compounds from algal biomass [103]. This method supplants conventional liquid extraction techniques, which are hindered by high solvent consumption and repetitive extraction steps [104]. The operational principle of MAE revolves around the application of electromagnetic waves to induce cellular structural changes. During microwave-assisted extraction (Fig. 3), microwave radiation interacts with polarizable compounds and dipoles present in a polar solvent. This interaction causes rapid oscillations in the direction of the electromagnetic fields, leading to the heating of polar solvent molecules aligned with the varying electric field. Conversely, non-polar solvents lacking polarizable groups exhibit lower heating efficiency. The thermal effects occur primarily at the molecular surface and a fraction of the sample, with the remaining portion heated through conduction. Consequently, a fundamental limitation of MAE is its inefficiency in uniformly heating large samples or agglomerates of smaller samples. Increasing the power of microwave sources has been proposed to enhance penetration depth; however, it should be noted that microwave radiation diminishes exponentially upon entering solid substances that absorb microwaves [105].

According to Kadam et al. [103], microwave radiation disrupts hydrogen bonds and facilitates the migration of dissolved ions during MAE extraction processes. Current literature underscores MAE's efficacy in extracting a variety of compounds including lipids (e.g., fatty acids, sterols), pigments (e.g., astaxanthin, fucoxanthin, chlorophylls), and phenolic compounds, typically employing organic solvents for extraction. Water, recognized for its effectiveness and environmental compatibility, is commonly used as a solvent for extracting polysaccharides such as fucoidan and agarose. The performance of the MAE system is influenced by critical parameters such as power, duration, algae species, and temperature settings [104], [106].

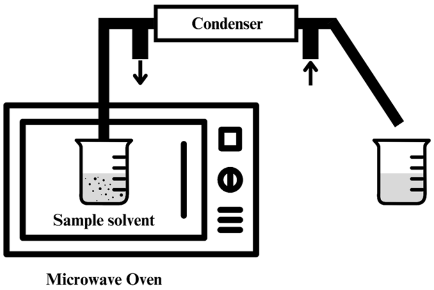

Fig. 3 Set-up for Microwave Assisted Extraction

D. Ultrasound-Assisted Extraction (UAE)

Ultrasound-Assisted Extraction (UAE) is recognized as a cold extraction technique due to its relatively low operating temperatures that ensure the stability of extracted compounds throughout the process (Fig. 4). This method offers several advantages over traditional extraction methods, including the reduction or elimination of hazardous chemical solvents, making it environmentally friendly and cost-effective by eliminating the need for additional energy to separate stages and remove solvents. UAE also facilitates rapid and consistent extractions within minutes, enhancing reproducibility, simplifying handling and work-up procedures, increasing the purity of the final product, and minimizing wastewater generated post-treatment.

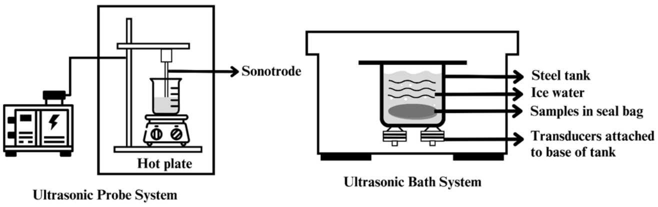

Fig. 4 Set-up for Ultrasonic Assisted Extraction

The mechanism of Ultrasound-Assisted Extraction (UAE) harnesses ultrasonic energy in conjunction with solvents to extract target chemicals from various plant matrices [107]. Ultrasonic waves, characterized by frequencies exceeding 20 kHz beyond the audible range of human hearing (20 Hz to 20 kHz), propagate through solid, liquid, or gaseous mediums, inducing cycles of compression and rarefaction. These waves create cavitation bubbles during rarefaction phases where the negative pressure exceeds molecular attraction forces, causing molecules to separate and disperse. The resulting macro-turbulence, high-velocity inter-particle collisions, and agitation within micro-porous matrix particles or cell walls facilitate solvent penetration, thereby initiating efficient extraction [108].

For instance, research has demonstrated the efficacy of UAE in extracting polymers from various plant materials, significantly reducing extraction times while enhancing overall yield of targeted components compared to conventional methods [109]. Dobrinčić et al. [110] utilized Ultrasound-Microwave-Assisted Extraction (UMAE) to maximize yields of bioactive fucose-sulfated polysaccharides from brown algae, demonstrating that extraction efficiency is influenced by ultrasound amplitude and duration. Their findings underscored the utility of UAE in optimizing the extraction of bioactive polysaccharides from diverse macroalgal species [111]. Table 1 summarizes different extraction methods for seaweed compounds and their respective yields.

TABLE I
GREEN EXTRACTION METHODS FOR SEAWEED COMPOUNDS

Extraction Method	Macroalgae	Seaweed composition	References
Enzymatic extraction: Carbohydrases (viscozyme) & proteases	Red seaweed Brown seaweed Green seaweed	Red seaweed: sulfated polysaccharides (carrageenan). Green seaweed: cellulose and xyloglucans. Brown seaweed: laminaran, alginate, and fucoidans.	[112]
Supercritical carbon dioxide (SD-CO2) extraction	Brown seaweed (Undaria pinnatifida)	Extracted seaweed oil: Fucoxanthin Beta-carotene polyunsaturated fatty acids (PUFAs) (arachidonic acid &	[113]

Extraction Method	Macroalgae	Seaweed composition	References
		eicosapentaenoic acid (EPA))	
Supercritical carbon dioxide (SD-CO2) extraction	Alaria esculenta, Laminaria digitata and Ascophyllum nodosum	β-carotene Carbohydrates proteins toxic metals (arsenic)	[114]
Ultrasound and membrane ultrafiltration	*Laminaria digitata*	Laminaria	[115]
Hydrodynamic cavitation (HDC)	Brown seaweed (*Alaria esculenta)*	High purity and recovery rate achieve: Laminarin Alginate Mannitol Protein	[116]
Enzymatic extraction : Commercial recombinant alginate lyases (PL7 and PL17)	Brown seaweed (*Saccharina latissima* & *Alaria esculenta*)	Fucoidan	[117]
Enzyme-assisted extraction (EAE) and water extraction (WE)	*Solieria chordalis*	3-Acetic Acid (IAA) 1-Amino-1-Cyclopropane-Carboxylic Acid (ACC) Salicylic Acid (SA)	[118]
Microwave-assisted extraction (MAE)	Red seaweed (Kappaphycus Alvarezii)	Carrageenan	[119]
Pressurized-water carrageenan extraction (PWCE)	Red seaweed (Kappaphycus Alvarezii)		
Pressurized liquid extraction (PLE)	Ceramium virgatum U. lactuca P. pavonica	Protein Sugar Phenolic content Phlorotannins	[120]
Methanolic extract	Sargassum polycystum	Terpenoid Saponin Phlobatannin Cardiac glycosides Phenolic Flavonoid	[121]

E. Macroalgae as the Powerhouse of Antioxidant and Antibacterial Properties

Seaweed's potential as a sustainable packaging material stem from its unique attributes, particularly its rich content of antioxidants and antibacterial compounds. These characteristics are increasingly recognized for their ability to enhance and innovate packaging applications. Current research is primarily focused on advancing sustainable packaging by integrating natural antioxidants and antibacterial properties, potentially replacing synthetic additives commonly used in the food industry. Synthetic preservatives, such as antimicrobials (e.g., potassium sorbate, sodium nitrite, sorbic acid) and antioxidants (e.g., butylated hydroxyanisole (BHA), butylated hydroxytoluene (BHT), tertbutyl hydroquinone (TBHQ)), are extensively employed but have raised concerns. Studies have suggested that synthetic antioxidants like BHA and BHT may exhibit slight carcinogenic properties in animal models at high doses. Consequently, regulatory bodies in regions such as the European Union, Japan, and Canada have imposed restrictions on compounds like TBHQ due to potential genotoxicity [120].

Research indicates that macroalgae, commonly referred to as seaweed, are abundant sources of bioactive compounds known for their robust antioxidant and antibacterial properties. The use of seaweed extracts as natural antioxidants and antibacterial agents is well-established across pharmaceuticals, biomedical applications, packaging industries, and food sectors. Seaweed-derived pigments such as phycoerythrin, phycocyanin, flavonoids, and polyphenolic compounds have gained attention due to their antioxidant capabilities [122]. Polyphenols, characterized by multiple phenol groups, are prevalent in seaweed extracts and contribute to their coloration. These compounds play crucial roles in maintaining algae's physiological integrity, providing defense against microbial threats, and protecting against oxidative stress and nutrient fluctuations [123].

Polyphenols exert antioxidant effects through various mechanisms, including their ability to act as reducing agents, hydrogen donors, singlet oxygen quenchers, metal chelators, and reducers of ferryl hemoglobin [124]. Their conjugated rings and hydroxyl groups facilitate antioxidant activity by effectively neutralizing and stabilizing free radicals involved in oxidative reactions [125]. Numerous studies have demonstrated a direct correlation between the total polyphenol content of seaweeds and their antioxidant capacity [126], [127]. Brown seaweeds are known to contain various phenolic components such as phenolic acids, flavonoids, bromophenols, lignans, and phlorotannin. Common phenolic compounds found in brown seaweeds include catechol, chlorogenic acid, quercetin, ferulic acid, and caffeic acid [128], [129].

Studies by Nofal et al. [130] have highlighted the presence of polysaccharides, catechic tannins, quercetin, genistein, polyterpene sterols, saponins, and phenolic substances in brown seaweeds, underscoring their potent antioxidant and antibacterial properties. These antioxidants effectively mitigate reactive oxygen species (ROS) during oxidation processes due to their strong affinity for oxidative agents. Thus, seaweeds represent a promising avenue for sustainable packaging solutions due to their natural abundance of antioxidants and antibacterial compounds. Continued research into harnessing these properties not only aims to reduce reliance on synthetic additives but also explores novel applications in various industries, contributing to both environmental sustainability and human health.

In a comprehensive study conducted by Premarathna et al. [131], the antioxidant properties of seaweed extracts, particularly those containing polysaccharides like carrageenan and xylan, were meticulously evaluated. This study focused on four species of red seaweed: Chondrus crispus (CC), Ahnfeltiopsis devoniensis (AD), Sarcodiotheca gaudichaudii (SG), and Palmaria palmata (PP). The methodologies employed included the DPPH (2,2-diphenyl-1-picrylhydrazyl radical) assay, ABTS (2,2-azino-bis-[3-ethylbenzothiazoline-6-sulfonic acid]) assay, superoxide dismutase (SOD) inhibition assay, ferric-reducing power in FRAP (Ferric-reducing Antioxidant Power) assay, and the hydroxyl radical (OH) scavenging capacity assay. Among the seaweed extracts analyzed, A. devoniensis (comprising a hybrid carrageenan with both iota and kappa forms) exhibited the highest antioxidant activity, whereas P. palmata (rich in xylans) demonstrated the lowest activity.

In another investigation, Keramane et al. [120] explored the antioxidant and antibacterial properties of hydroethanolic extracts from six algae species found on the west coast of Algeria. These species included Scoparia, Cystoseira mediterranea, Ulva lactuca, Ulva intestinalis, and Ceramium virgatum. The findings revealed that the extract of P. pavonica displayed superior antioxidant capacity, effectively inhibiting ABTS radical (1.16 ± 0.023 mmol TE/g) and achieving a 50% inhibition of DPPH (IC50 = 57.03 ± 1.28 µg/mL). Cystoseira mediterranea exhibited the most potent antibacterial activity, with the lowest minimal inhibitory concentrations observed against Salmonella typhi (0.83 ± 0.14 mg/mL), Escherichia coli (4.66 ± 0.57 mg/mL), Vibrio cholera (1.08 ± 0.14 mg/mL), and Candida albicans (2.16 ± 0.28 mg/mL).

Afrin et al. [126] conducted further investigations into the antioxidant and antibacterial characteristics of crude seaweed extracts. The study revealed that the methanolic extract of Sargassum muticum exhibited significantly elevated levels of total antioxidant activity (TAA) ($P < 0.05$). Additionally, the methanolic extracts of Padina tetrastromatica and Sargassum muticum showed substantial ($P < 0.05$) antioxidant activity against DPPH and ABTS radicals. In contrast, the acetone extract of Bifurcaria bifurcata displayed the highest effective concentration for CUPRAC activity (ECA0.50 value of 0.78 mg/mL). Furthermore, the ethanolic extracts of Padina tetrastromatica, Sargassum muticum, and Hypnea clathratus exhibited larger inhibitory zones against all tested bacterial strains compared to other seaweed extracts, highlighting the superior antioxidant and antibacterial properties of brown seaweeds. These studies collectively underscore the significant potential of various seaweed species in providing antioxidants and antibacterial properties, which are crucial for developing bio-based packaging materials with enhanced functionality. The evaluation of different extraction methods, such as hydroethanolic and methanolic extraction, and the comparative analysis of different seaweed species provide a comprehensive understanding of the bioactive properties inherent in seaweeds.

The antioxidant activities observed in seaweed extracts are primarily attributed to the presence of polysaccharides such as carrageenan and xylan, which are known for their free radical scavenging abilities. The variation in antioxidant activity among different species can be linked to the distinct compositions and structures of these polysaccharides. For instance, the high antioxidant activity of A. devoniensis can be attributed to its unique hybrid carrageenan composition, which effectively neutralizes free radicals and inhibits oxidative processes. In the context of antibacterial activity, the effectiveness of seaweed extracts against various bacterial strains highlights their potential as natural preservatives in food packaging. The findings from Keramane et al. [120] and Afrin et al. [126] indicate that specific seaweed species possess potent antibacterial properties that can be harnessed to inhibit the growth of pathogenic bacteria, thereby extending the shelf life of food products. The integration of seaweed extracts into bio-based packaging materials offers a sustainable alternative to synthetic additives, aligning with the growing demand for environmentally friendly and health-conscious packaging solutions. The antioxidant properties of these extracts can protect food products from oxidative damage, while their antibacterial properties can prevent spoilage and contamination, ensuring food safety and quality.

Using polysaccharides from seaweed like alginate, agar, and carrageenan for biodegradable films offers a new method for sustainable packaging. These polysaccharides, owing to their film-forming capabilities and bioactive properties, can create functional packaging materials that are not only biodegradable but also enhance the preservation of food products. The application of advanced extraction techniques, such as supercritical fluid extraction and enzymatic-assisted extraction, can further optimize the yield and functionality of seaweed extracts. These methods can preserve the integrity of bioactive compounds, ensuring that the extracted polysaccharides retain their antioxidant and antibacterial properties. Furthermore, the studies by Premarathna et al. [131], Keramane et al. [120], and Afrin et al. [126] provide compelling evidence of the potential of seaweed extracts as functional ingredients in bio-based packaging materials. The antioxidant and antibacterial properties of these extracts can significantly enhance the shelf life and safety of food products, offering a sustainable and effective alternative to conventional packaging solutions. The continued exploration and optimization of extraction methods, combined with a deeper understanding of the bioactive properties of different seaweed species, will pave the way for innovative applications of seaweed in the food packaging industry.

F. Application of Macroalgae for Packaging

In Sultan et al. [132] study, *Dillenia serrata* peel pectin and curcumin were blended in varying amounts to generate a carrageenan-based edible film using the casting process. The results revealed that the edible film with the highest pectin and curcumin content had the lowest thickness and WVTR. When more curcumin was added to the biopolymer matrix, all films had a lower inhibitory zone for Escherichia coli than Staphylococcus aureus. These findings indicated that carrageenan-based edible film containing pectin and curcumin increased overall performance. This approach could be an effective strategy for encouraging the long-term use of indigenous fruit wastes (Dillenia serrata fruit peel) for the production of edible packaging film.

Similarly, Zhoa et al. [133] The characteristics of agar/gelatin (AG/GE) composite film, agar/gellan gum (AG/GG), and agar/κ-carrageenan (AG/KC) composite films were examined using CNC and calcium chloride. The results showed that the three produced nanocomposite films had dense and smooth surface structure, and their tensile strength (TS), elongation at break (EB), and light transmittance were greater than 60 MPa, 21%, and 80% at 660 nm. These three prepared films not only had better comprehensive properties than previous studies, but they also had edible, good light transmittance, and heat seal performance, as well as better fresh keeping performance than plastic-based food packaging film when used to preserve strawberries using packaging or coating methods.

The development of biocomposite films with active components like W-GeFS and SSEO highlights the growing interest in enhancing food packaging materials' functionality through natural additives. These studies exemplify the potential of bio-based films to not only extend the shelf life of food products but also to provide additional health benefits by incorporating natural antioxidants and antimicrobials. The incorporation of natural extracts into biocomposite films can significantly influence their physical, mechanical, and antibacterial properties, making them suitable for various applications in the food industry. The ability of SRC films with W-GeFS to effectively inhibit microbial growth on chicken breast samples demonstrates their potential as active packaging materials. This aligns with the broader objective of developing sustainable and functional packaging solutions that enhance food safety and quality.

Similarly, the CMC-agar films with SSEO showcase the importance of optimizing the concentration of natural additives to achieve the desired balance of antibacterial activity and mechanical properties. These studies highlight the promising advancements in the development of bio-based packaging films with enhanced functionalities. The use of natural extracts such as W-GeFS and SSEO not only improves the antimicrobial and antioxidant properties of the films but also contributes to their overall performance as sustainable packaging solutions. Future research should continue to explore the synergistic effects of various natural additives and their interactions with different biopolymer matrices to further optimize the properties and applications of bio-based packaging materials. These innovations are crucial for advancing sustainable practices in the food packaging industry and meeting the growing consumer demand for eco-friendly and health-promoting products.

Gemida et al. [134] conducted a study to assess the shelf life of tomatoes (Solanum lycopersicum) in various postharvest treatments in terms of color, firmness, percent weight loss, and tomato weight. Seaweed treatment at 3% concentration, hot water treatment for 20 minutes, and UV-C light treatment for 20 minutes had the same effect but significantly maximized the shelf life of tomatoes than tap water treatment during 30 days of storage; seaweed treatment at 3% concentration significantly delays the color of the shelf life of tomatoes among treatments during 30 days of storage; seaweed treatment is significantly firmer than tap water treatment yet similar to UV-C light and hot water treatments. Seaweed treatment, UV-C light treatment, and hot water treatment all have similar effects on the firmness and shelf life of tomatoes after 30 days of storage. Seaweed treatment at 3% concentration results in lower percent weight loss than tap water and hot water treatment but is comparable to UV-C light treatment. UV-C light and seaweed treatment had comparable benefits on tomato weight loss. Both may help reduce tomato weight loss during storage.

In another study, Zhao et al. [135] studied the effect of chitosan and alginate (CH-SA) coating combined with the cell-free supernatant of Streptococcus thermophilus FUA329 (CFS) as a preservative on the quality of white shrimp (Litopenaeus vannamei) refrigerated at 4°C for 0, 3, 6, 9, 12, 15 days. When compared to the control, the CFS-CH-SA coating effectively inhibited microbial growth, total viable count, and chemical buildup. Furthermore, the CFS-CH-SA coating improved the texture and sensory properties of shrimp during storage. The coated shrimp showed a considerable reduction in water loss ($p<0.05$). The combination of CH-SA coating with CFS treatment can increase the shelf life of shrimp.

Further emphasizing the potential of red seaweed, Gracilaria gracilis has been noted for its extensive biological functions, including significant antioxidant activity [136]. This marine biomass boasts a high concentration of total phenols and impressive radical scavenging activity, comparable to that of the synthetic food additive butylated hydroxytoluene (BHT). Such properties make red seaweed bioactive compounds, in combination with Porphyridium EPS, potentially effective for preserving shellfish products, offering an alternative to synthetic additives.

Baek et al. [137] investigated an innovative edible coating solution incorporating nanoparticles with grapefruit seed extract (GSE) as an antibacterial agent and alginate as the coating agent. The study's results indicated that shrimp coated with 1% alginate showed significant improvements in quality preservation during storage compared to uncoated shrimp. The alginate coating effectively inhibited degradation, microbial growth, melanosis, and weight loss by limiting oxygen exposure. The addition of GSE further enhanced these protective effects, with the combination of 1% alginate and 1% GSE nanoparticles showing the most significant reductions in total viable bacterial counts (TVBC), superior sensory scores, and lower TVB-N values ($p < 0.05$). The small size of the nanoparticles ensured even distribution, minimizing any adverse effects on flavor. The study concluded that nanoparticles comprising 1% alginate and 1% GSE are highly effective as edible coatings for extending the shelf life of prawns, although further research is needed to fully understand the underlying mechanisms and broader impacts of nanoparticle use.

Collectively, these studies underscore the significant potential of seaweed-based biopolymers and edible coatings in enhancing the shelf life and quality of various food products. Seaweed-derived substances such as alginate, agar, carrageenan, and exopolysaccharides exhibit strong film-forming, antimicrobial, and antioxidative properties, making them ideal for sustainable food packaging applications. The utilization of seaweed in edible coatings is particularly promising given the current environmental concerns associated with synthetic packaging materials. Seaweeds such as Kappaphycus alvarezii, Sargassum tenerrimum, and Gracilaria gracilis offer a renewable and biodegradable alternative, aligning with global efforts to reduce plastic waste and promote sustainability in food packaging. Furthermore, the incorporation of natural antibacterial agents like grapefruit seed extracted into seaweed-based coatings can enhance the microbial safety and extend the shelf life of perishable products without compromising sensory qualities. The research highlights the multifaceted benefits of seaweed-based biopolymers and edible coatings, providing a robust foundation for future advancements in sustainable food packaging technologies. These innovations not only address critical food safety and preservation challenges but also contribute to broader environmental sustainability goals, demonstrating the transformative potential of marine biomass in the food industry.

Previous research has highlighted the significant antioxidant and antibacterial properties of various brown seaweeds, including Padina tetrastromatica, Sargassum muticum, and Spatoglossum asperum [138]. Notably, bioactive macromolecules such as fucoidan and sulfated polysaccharides, which are prevalent in brown seaweeds, exhibit potent antibacterial activities against several bacterial pathogens. These pathogens include Vibrio spp., Staphylococcus sp., Escherichia coli, Aeromonas hydrophila, *Enterobacter sp.,* and *Pseudomonas aeruginosa,* among others [126]. The presence of phytonutrients such as flavonoids, steroids, saponins, and tannins has been confirmed in selected seaweeds, demonstrating their broad-spectrum bioactivity [135]. Specifically, the antibacterial and antifungal properties of Kappaphycus alvarezii were found to be more effective against common pathogens compared to S. tenerrimum. Evaluations of water loss, texture, ascorbic acid concentration, juice content, total soluble solids (TSS), total acidity, and the TSS/total acidity ratio revealed that K. alvarezii was superior in maintaining the quality attributes of tomato fruits, thus supporting fruit quality throughout storage.

Jayapala et al. [139] conducted a comprehensive study characterizing and quantifying the phenolics, hydrocolloids, lipids, and carotenoids of the marine brown algae Padina tetrastromatica. They also investigated the antioxidant and antidiabetic properties of the phenolic compounds. Using UPLC-HRMS/MS analysis, they identified several free phenolics, including quercetin derivatives, luteolin, genistein, and a hydroxyl-ferulic acid derivative. The bound phenolics included luteolin, an acacetin derivative, a dioxinodehydroeckol derivative, and rosmarinic acid. The phenolic extracts from P. tetrastromatica demonstrated notable radical scavenging activities, with values of 10.83 ± 2.81 μg/mL and 58.85 ± 2.28 μg/mL using the 2,2′-azino-bis (3-ethylbenzothiazoline-6-sulfonic acid) (ABTS) and 2,2-diphenyl-1-picryl-hydrazyl-hydrate (DPPH) assays, respectively. Additionally, the total antioxidant activity of these phenolics was measured at 29.13 ± 2.31 μg ascorbic acid equivalent, and their reductive capability was found to be 32.39 ± 3.11 μg quercetin equivalent. The extracts exhibited half-maximal inhibitory concentrations (IC50) for α-amylase and α-glucosidase at 47.2 ± 2.9 μg and 28.8 ± 2.3 μg, respectively. The study also identified fatty acids such as methyl-palmitate and methyl-palmitoleate in the neutral, glyco, and phospholipid fractions of the total lipids, which constituted 0.82% of the seaweed's composition. The bioactive components of P. tetrastromatica included fucoxanthin (96.66%), various polysaccharides (mg/g dry weight), laminarin (14.78%), fucoidan (1.38%), and alginate (70.16%). These components contribute to the seaweed's high nutritional density, suggesting its potential applications in food and pharmaceutical industries.

The extensive bioactivity of brown seaweeds underscores their potential as sustainable sources of bio-based packaging materials. The antioxidant and antibacterial properties of these seaweeds can be leveraged to enhance the shelf life and safety of perishable goods. Specifically, the bioactive compounds in brown seaweeds could be incorporated into packaging films to inhibit the growth of spoilage microorganisms and pathogens, thereby preserving food quality and extending shelf life. Moreover, the use of green extraction methods such as supercritical fluid extraction, enzymatic-assisted extraction, microwave-assisted extraction, and ultrasound-assisted extraction can optimize the yield and maintain the integrity of these bioactive compounds. These methods are advantageous over conventional techniques due to their low solvent usage, high selectivity, quick processing, and reduced extract degradation.

The regulatory aspects concerning the incorporation of macroalgae compounds into food packaging materials are also critical. Ensuring that these bio-based materials comply with food safety standards is essential for consumer acceptance. The widespread consumption of macroalgae in countries like China, Japan, and Korea demonstrates its safety and familiarity, paving the way for broader acceptance of macroalgae-based packaging in global markets. Therefore, macroalgae, particularly brown seaweeds, offer a sustainable and eco-friendly resource for developing bio-based packaging materials. The antioxidant and antibacterial properties of these seaweeds, combined with advanced extraction methods, can significantly enhance the quality and shelf life of packaged foods. Future research and development should focus on optimizing extraction techniques, ensuring regulatory compliance, and exploring the full potential of macroalgae in sustainable packaging solutions.

In a study conducted by Sáez et al. [140], the efficacy of various algal extracts—Crassiphycus, Ulva, Arthrospira platensis, and Haematococcus—was evaluated as supplements for the preservation of rainbow trout fillets. The extracts were prepared using different water-to-ethanol ratios from the four algae species. Among these, Ulva extract obtained with 80% ethanol demonstrated the highest ferric-reducing antioxidant power (FRAP). Additionally, an aqueous extract of Ulva showed significant FRAP activity, which was consistent with its high total phenolic content. The Crassiphycus extract, also with 80% ethanol, exhibited stronger radical scavenging activity (DPPH), attributable to its high total carotenoid concentration. All algal extracts effectively delayed microbial growth and lipid oxidation in trout filets during cold storage compared to control samples. Furthermore, they improved textural metrics, with Arthrospira platensis and Haematococcus extracts showing the most pronounced benefits. The natural origin and large-scale growth feasibility of these algal extracts make them promising candidates as fish-preserving agents in the food industry.

In another study, K. *alvarezii* (K) biomass-based thin films incorporated various natural additives, including Azadirachta indica oil (K1), A. indica leaf extract (K2), Citrus limon leaf extract (K3), A. indica gum (K4), Prunus amygdalus gum (K5), Moringa indica gum (K6), and a combination of A. indica leaf extract and oil (K7). The antibacterial activity of the K series films, both without glycerol (K) and with glycerol (KG), was evaluated against Staphylococcus aureus. The KG series films exhibited maximum inhibition zones of 12 mm (KG7), 11 mm (KG6), 10 mm (KG), and 9 mm (KG1, KG4, KG5). Similarly, the K series films demonstrated zones of inhibition of 9 mm (K, K1, K7) and 10 mm (K2), indicating high antibacterial activity. These biofilms were effective in prolonging the shelf life and preserving the quality of tomatoes for up to 14 days at room temperature [141].

Brown seaweed has a high bioactivity potential and can give health advantages as a functional food element. They were examined for metabolite profile, biochemical activities (including total antioxidant, reducing, scavenging, and anti-proliferative properties), and total phenolic and flavonoid content. All four brown seaweeds shown concentration-dependent antioxidants, reducing, and scavenging activity. Multivariate correlation research revealed a favorable relationship between total phenolic and flavonoid content and biochemical activities (total antioxidant, scavenging, and reducing) in all brown seaweeds. Overall, S. asperum has high levels of total flavonoid and phenolic compounds, as well as possible antioxidant, scavenging, and reducing properties. The study validated the nutraceutical potential of S. asperum, which could be a viable functional food ingredient [142]. Another study focused on the use of seaweed powder as a bio-filler in alginate films. Regardless of the filler content or particle size, the incorporation of seaweed powder resulted in films with improved barrier and antioxidant properties, although their strength diminished due to uneven filler distribution within the alginate matrix. Increased filler loading enhanced the antioxidant and barrier characteristics. Additionally, the study found that combining seaweed with plasma-activated water (PAW) can enhance the functionality and bioactivity of alginate films, making them suitable for potential food packaging applications [143].

Active edible coatings derived from microalgal exopolysaccharides (EPS) and enriched with various concentrations of red seaweed extract (RSE) (0.5%, 1%, and 1.5% w/v) were developed. These coatings were effective in inhibiting bacterial species, particularly psychotropic bacteria. Furthermore, shrimp samples coated with EPS + RSE exhibited lower polyphenol oxidase activity and better oxidative stability ($p < 0.05$) throughout their shelf life. The EPS coatings significantly improved the hardness and color of shrimp without negatively impacting their initial sensory attributes. The results indicated that applying EPS-based coatings led to an improvement in quality and an extension of the shelf life of refrigerated shrimp [135]. The research underscores the importance of macroalgae extracts in the food industry due to their sustainable and environmentally friendly nature. These studies collectively highlight the potential of various algal extracts and seaweed-based films to serve as natural preservatives and active packaging materials, offering benefits such as enhanced antioxidant activity, antibacterial properties, and improved mechanical qualities. The utilization of these natural resources aligns with the growing demand for sustainable and eco-friendly solutions in food preservation and packaging, promoting a healthier and more sustainable approach to food safety and quality maintenance.

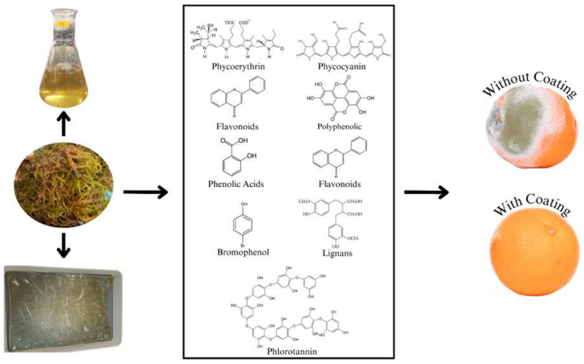

Fig. 5 Application of Macroalgae in food industry

G. Regulation of Compatibility Macroalgae with Food Products

Seaweed-based packaging has garnered increasing attention as a viable and eco-friendly alternative to conventional plastic packaging. This popularity stems from seaweed's natural growth patterns, its inherent sustainability, its nutritional benefits, and its polysaccharide content. However, the adoption of seaweed-based packaging must rigorously comply with regulatory standards to ensure it meets food contact material (FCM) safety criteria. A crucial aspect of the compatibility of seaweed-based packaging materials is their biocompatibility and non-toxicity. This compatibility ensures that these materials do not leach hazardous substances into food products. Additionally, it is imperative that seaweed-derived materials adhere to safety guidelines specifically designed for food packaging applications. Regulatory compliance must prioritize the safety of these applications because legislative frameworks play an essential role in guaranteeing that seaweed-based packaging aligns with food safety standards.

The European Union Regulation on Food Contact Materials, for instance, emphasizes risk assessment and safety. Compliance with this regulation entails adhering to maximum permissible levels of pollutants such as cadmium and arsenic, which is vital for ensuring safety. According to a consensus statement on the migration of hazardous chemicals from packaging materials into food [144], the chemical safety of recycled non-plastic materials is sometimes overlooked during development. Furthermore, the existing EU regulatory framework for food contact materials is deemed insufficient for adequately protecting consumers. As a result, many individuals are inadvertently exposed to chemicals that can lead to chronic health issues, with children being particularly vulnerable. The EU Regulation on Food Contact Materials (EC/1935/2004) mandates that the use of FCMs must be based on thorough scientific risk assessments. The regulation stipulates that "materials do not release their constituents into food at levels harmful to human health" (Article 3(1)(a)). Seaweeds are increasingly being utilized as FCMs due to their numerous benefits. Nevertheless, they can accumulate several hazardous compounds and toxic metals, including mercury, lead, and arsenic [145]. Cadmium, for example, naturally accumulates in seaweed. Consequently, food supplements containing dried seaweed or its derivatives may have higher cadmium levels compared to other food supplements.

Commission Regulation (EC) No 629/2008, which amends Regulation (EC) No 1881/2006, sets the maximum permissible level for certain contaminants in foodstuffs, allowing up to 3 mg of cadmium per kg of dry seaweed [146]. Additionally, Commission Regulation (EU) No 1275/2013, which amends Annex I to Directive 2002/32/EC of the European Parliament, permits a maximum arsenic content of 40 mg/kg and 10 mg/kg (at a moisture content of 12%) in complementary seaweed feed meals, respectively [147]. However, other regions, including South America, the USA, and several Asian countries, lack specific legislation regulating the concentration of toxic substances in seaweed or seaweed-derived products. The European Commission has established maximum levels for cadmium (3.0 mg/kg), mercury (0.1 mg/kg), and lead (3.0 mg/kg) in seaweed used as food supplements predominantly composed of dried seaweed (Regulation (EC) No. 1881/2006). Nonetheless, there are no established threshold values for seaweed as a general food source. For animal feed, the European Directive 2002/32/EC sets maximum levels for total arsenic (40 mg/kg) and inorganic arsenic (2.0 mg/kg)..

Marine macroalgae, a category that includes seaweeds, may also contain significant concentrations of iodine, often exceeding 2000 mg/kg dry weight [148]. The EFSA Panel on Dietetic Products, Nutrition, and Allergies recommends a daily iodine intake of 150 µg for individuals to maintain optimal health. However, excessive iodine consumption can lead to health issues related to both iodine deficiency and excess, such as hypothyroidism and goiter. To prevent these conditions, the EFSA recommends a daily iodine intake ranging from 150 to 600 µg for adults. Thus, while seaweed-based packaging offers a promising sustainable alternative to traditional plastic packaging, its implementation necessitates stringent adherence to regulatory standards to ensure food safety. This involves rigorous risk assessments and compliance with maximum permissible levels of hazardous substances, as outlined by relevant regulations such as the EU Regulation on Food Contact Materials. Ensuring the safety and compatibility of seaweed-based packaging materials is essential for protecting consumer health and fostering the adoption of sustainable packaging solutions.

Numerous studies have examined the distribution of metals and metalloids in seaweed, revealing that the presence of heavy metals and associated health risks varies significantly among different seaweed species [149], [150], [151], [152]. Despite this, most countries lack regulations on the permissible levels of heavy metals in seaweed. The European Commission has established maximum levels for cadmium (3.0 mg/kg), mercury (0.1 mg/kg), and lead (3.0 mg/kg) in seaweeds used as food supplements composed primarily or entirely of dried seaweed, as per Regulation (EC) No. 1881/2006. However, no such thresholds have been set for seaweed intended as food products [153]. In China, the National Standard for Food Safety (GB 2762–2017) specifies a maximum level for lead (2.0 mg/kg) in dried seaweed but does not impose limits for other heavy metals [154]. Furthermore, Regulation (EC) No. 710/2009, which governs organic aquaculture and seaweed production, emphasizes that the aquatic growing environment is critical for producing safe, high-quality products with minimal environmental impact [155].

The globalization of markets and frequent food safety alerts have heightened consumer awareness regarding the necessity of food traceability. To ensure food safety, regulatory frameworks must include traceability of the geographic origin of seaweed and establish maximum permissible levels of chemical elements within them [156], [157], [158]. This would provide consumers with assurance about the safety and quality of seaweed products and address the complex variability and health risks associated with heavy metal contamination in different seaweed species. Thus, while the European Commission and China have set some regulations regarding heavy metal levels in seaweeds, comprehensive standards are still lacking globally. Establishing robust regulatory requirements, including clear traceability and maximum levels of contaminants, is essential for safeguarding public health and maintaining the integrity of seaweed products in the global market.

H. Consumer Perception and Acceptance

The perception of consumers refers to how individuals perceive and comprehend information about products and services. Understanding client acceptability is crucial for businesses aiming to enhance their development efforts, procedures, and innovations [159]. This understanding of consumer acceptance provides a deeper insight into customer behavior and preferences [160]. Previous research has established that customer approval significantly influences the success of new products or innovations, with 7 out of 10 new products' success being heavily impacted by it [161]. For instance, Alfaridi et al. [162] noted that the innovation of edible seaweed packaging remains largely unrecognized. Despite widespread awareness of the toxicity of plastic and its severe environmental impact, most companies and manufacturers continue to use it for packaging, especially food.

Several factors influence consumer perception of seaweed-based packaging, as illustrated in Figure 5. These factors include awareness of environmental and health concerns, cultural context, and aesthetic appeal. Norton et al. [163], in their survey study, found that consumers often experience confusion about recycling and possess limited awareness of sustainable materials. Therefore, focused education and guidance are necessary to assist consumers in making informed choices. For environmentally conscious consumers, seaweed packaging may appeal due to its renewable and biodegradable nature, which aligns with their values. Seaweed's potential to provide moisture and gas barrier qualities that can be customized for specific food products enhances its attractiveness.

The environmental impact of packaging waste is significant, as reported by Wang et al. [164] and Duarte et al. [165]. Packaging manufacturing, usage, disposal, and recovery generate vast amounts of waste and consume raw materials, water, and energy, resulting in emissions that contribute to global warming. Thus, reducing packaging waste is critical to achieving sustainability and cleaner production goals. Consumers perceive the application of sustainable packaging as an ethical decision that helps reduce plastic waste. Health considerations also influence consumer perceptions. Some customers associate seaweed with health benefits, given its rich content of minerals, antioxidants, and other beneficial compounds [166]. This positive perception can encourage the use of seaweed in food packaging. Cultural context plays a role in acceptance, with consumers in countries like Japan and Korea, where seaweed is a staple, being more open to its use. In contrast, in regions where seaweed is less common, education and marketing are essential to enhance acceptance. Visual appeal is another crucial factor in consumer response to seaweed-based packaging. As with other technologies, the appearance of the package is essential to consumers. Acceptance increases when packaging is visually appealing and matches consumer aesthetic preferences [167]. Consumer acceptance is measured by individuals' willingness to adopt or use a product or technology. Factors such as sustainability and healthiness are important considerations. Consumers are more likely to accept seaweed-based packaging if they perceive more advantages than disadvantages.

Taste and odor are significant considerations for food packaging. Seaweed packaging must not adversely affect the taste or scent of food, as this could deter consumers from using it. Usability is also important; consumers appreciate packaging that is easy to handle and conforms to established behaviors, which increases acceptability. Assuring that the packaging will not harm food quality or introducing hazardous components is essential. Understanding consumer perceptions, overcoming acceptance barriers, and emphasizing the benefits of seaweed-based food packaging are essential for its successful implementation. Companies must focus on educating consumers about the environmental and health benefits, addressing cultural differences, ensuring the visual appeal of packaging, and maintaining the integrity of food quality. By doing so, they can enhance consumer acceptance and contribute to more sustainable and environmentally friendly packaging solutions.

IV. Conclusion

Macroalgae, rich in polysaccharides such as carrageenan, alginate, and agar, as well as various bioactive compounds, present a promising solution for application in food packaging, particularly in films and coatings designed to enhance the shelf life of fruits and vegetables. The utilization of macroalgae extracts as coatings has demonstrated significant potential in improving the quality of fresh produce. This improvement is attributed to the presence of natural polymers like agar and carrageenan, which exhibit antioxidant activity, antibacterial properties, and effective moisture barriers. Implementing macroalgae extracts on food surfaces offers several benefits, including enhanced preservation, improved visual appeal, and extended product viability. Due to their carbohydrate-rich cell walls, macroalgae species are particularly well-suited to produce biopolymer films. Polysaccharides such as fucoidan, laminarin, and alginate serve as the foundational components of these biopolymer films, providing structural integrity and functionality. Optimal processing methods are crucial to maximizing the yield of macroalgae extracts. For instance, supercritical fluid extraction (SFE) is an environmentally friendly technique that effectively recovers essential bioactive compounds from complex matrices. The incorporation of enzymes in the extraction process offers numerous advantages, including enhanced selectivity, higher yields, time efficiency, environmental sustainability, and safety for food and health applications. Moreover, microwave-assisted extraction (MAE) is recognized as a novel and ecologically benign method for extracting biologically active compounds from algal biomass. MAE is preferred over traditional liquid extraction methods, which often involve large quantities of solvents and repetitive extraction procedures, presenting several drawbacks. The sustainability of macroalgae as a resource underscores the importance of further research into their applications for extending the shelf life of fresh produce. As a renewable resource, macroalgae offers a viable and eco-friendly alternative to conventional food preservation methods. Their ability to form biopolymer films and coatings that enhance the quality and longevity of fresh produce makes them an attractive option for the food packaging industry. In conclusion, the application of macroalgae extracts in food packaging, specifically in the form of films and coatings, offers a multifaceted approach to enhancing the shelf life and quality of fresh produce. The inherent properties of macroalgae, including their rich polysaccharide content and bioactive compounds, provide significant benefits such as antioxidant and antibacterial activities, as well as moisture barrier properties. Advanced extraction techniques, including SFE and MAE, further optimize the recovery of these valuable compounds, contributing to the overall efficacy and sustainability of this approach. Given the increasing emphasis on sustainable resources and environmentally friendly practices, the potential of macroalgae in food packaging warrants continued research and exploration.

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