

International Journal of Advanced Biochemistry Research



ISSN Print: 2617-4693
ISSN Online: 2617-4707
NAAS Rating (2026): 5.29
IJABR 2026; SP-10(8): 1277-1289
www.biochemjournal.com
Received: 20-05-2026
Accepted: 23-06-2026

DR Bhaladhare
Department of Fish Processing
Technology, College of
Fisheries, Ratnagiri,
Maharashtra, India

PA Kamble
Department of Fish Processing
Technology, College of
Fisheries, Ratnagiri,
Maharashtra, India

TG Kazi
Department of Fish Processing
Technology, College of
Fisheries, Ratnagiri,
Maharashtra, India

P Sedyaaaw
Department of Fish Processing
Technology, College of
Fisheries, Ratnagiri,
Maharashtra, India

SV Bhor
Department of Fish Processing
Technology, College of
Fisheries, Ratnagiri,
Maharashtra, India

PA Valu
Department of Fish Processing
Technology, College of
Fisheries, Ratnagiri,
Maharashtra, India

SD Meshre
Department of Fish Processing
Technology, College of Fishery
Science, Udgir, Maharashtra,
India

P Sindhuja
Department of Fish Processing
Technology, ICAR- Central
Institute of Fisheries
Education, Mumbai,
Maharashtra, India

Corresponding Author:
DR Bhaladhare
Department of Fish Processing
Technology, College of
Fisheries, Ratnagiri,
Maharashtra, India

Seaweed polysaccharides as functional materials for edible films and coatings: A comprehensive review

DR Bhaladhare, PA Kamble, TG Kazi, P Sedyaaaw, SV Bhor, PA Valu, SD Meshre and P Sindhuja

DOI: <https://www.doi.org/10.33545/26174693.2026.v10.i8So.9603>

Abstract

Seaweeds have gained significant attention as sustainable and biodegradable resources for the development of edible biofilms and coatings in food packaging applications. The growing concerns regarding environmental pollution caused by conventional plastic packaging have accelerated research into renewable alternatives with enhanced functional properties. Seaweed-derived polysaccharides, including alginate, agar, carrageenan, fucoidan, laminarin, and ulvan, possess excellent film-forming, gelling, emulsifying, and biocompatible characteristics, making them suitable for edible coating formulations. These biofilms act as protective barriers against moisture loss, oxygen transfer, microbial contamination, and lipid oxidation, thereby improving food quality and extending shelf life. Recent advancements have focused on incorporating natural antioxidants, antimicrobial compounds, plant extracts, essential oils, and nanoparticles into seaweed-based coatings to enhance their mechanical, thermal, antioxidant, and antimicrobial properties. Applications have been successfully demonstrated in fruits, vegetables, seafood, meat products, and ready-to-eat foods. Furthermore, seaweed-based coatings contribute to active and intelligent packaging systems capable of monitoring food quality and freshness. Despite their promising potential, challenges such as high production costs, variability in raw materials, scalability, and optimization of barrier properties remain. This review highlights the sources, properties, applications, coating methods, performance characteristics, current trends, and future prospects of seaweed-derived edible biofilms, emphasizing their role as eco-friendly alternatives for sustainable food preservation and packaging systems.

Keywords: Seaweed polysaccharides, edible coatings, bioactive packaging, alginate and carrageenan, food preservation, sustainable food packaging

1. Introduction

Developing active food packaging is essential to delivering high-quality, safe food. Innovation in packaging technology has focused on creating packaging technologies that can actively support food safety. According to Chang *et al.*, (2023) ^[19], Irimia *et al.*, (2024) ^[40], Lima *et al.*, (2024) ^[51], Nasution *et al.*, (2023) ^[60], and others, active packaging is a type of packaging material that actively interacts with the internal environment of the packaged product in order to prolong shelf life, preserve quality, improve sensory qualities, and minimise food waste. Because of their special interaction with food goods, this packaging helps prevent perishable food from spoiling and enhances or maintains the safety and quality of food products (Drago *et al.*, 2023; Gengatharan & Rahim, 2023) ^[30, 79]. The presence of antimicrobial and antioxidant substances in the packaging material is one factor taken into account when creating such packaging (Nasution *et al.*, 2024; Yang *et al.*, 2024) ^[61, 74]. The packaging materials antimicrobial and antioxidant properties greatly lower the dangers to food safety (Gengatharan & Rahim, 2023) ^[79]. They can preserve the sensory qualities of fatty foods while shielding them from oxidation processes. Edible film is one type of active packaging that is now being developed extensively. During storage, these coatings can prevent microbial development, lipid oxidation, and nutritional breakdown by regulating the transfer and penetration of oxygen, water vapour, and active chemicals. By releasing active agents into the storage environment, adding natural active compounds to biodegradable polymers to create such packaging sheets can stop food from spoiling. The presence of antimicrobial and antioxidant substances in the packaging material is one factor taken into account when creating such packaging (Nasution *et al.*, 2024; Yang *et al.*, 2024) ^[61, 74].

The packaging's antimicrobial and antioxidant properties greatly lower the dangers to food safety (Gengatharan & Rahim, 2023) ^[79]. They can preserve the sensory qualities of fatty foods while shielding them from oxidation processes. Edible film is one type of active packaging that is now being developed extensively. During storage, these coatings can prevent microbial development, lipid oxidation, and nutritional breakdown by regulating the transfer and penetration of oxygen, water vapour, and active chemicals. By releasing active agents into the storage environment, adding natural active compounds to biodegradable polymers to create such packaging sheets can stop food from spoiling. Because organic phosphorus pollutants, such as organic phosphate antioxidants and organic phosphate esters, migrate from plastics to food, using plastic wrapping as food containers can also be harmful to your health. These substances can move to oily, alkaline, and acidic food mimics and are present in plastic packaging (Xing *et al.*, 2023) ^[73]. In response to customer requests for

environmentally friendly and sustainable solutions, active edible film offers a potentially safer and more natural substitute for food contact applications (Haridevamuthu *et al.*, 2024; Stanley *et al.*, 2022) ^[38, 70].

2. Seaweeds

In shallow waters at a depth of 180 meters, seaweeds are typically found on rocks, pebbles, shells, and marine plants. It is quite abundant and grows quickly. The primary uses of seaweeds are in food, medicinal, fertiliser, and animal feed. Since 1995, seaweed consumption has grown by roughly 176%. Seaweed cultivation is currently in demand because of its many uses, expensive cost (approximately USD 50-80/ton), and trend of being used as sustainable products. However, because they are now restricted to coastal regions, seaweed farming and production are extremely limited (Nakhate *et al.*, 2021) ^[80]. Figure 1 illustrates the process for creating these seaweed-based FCMs.

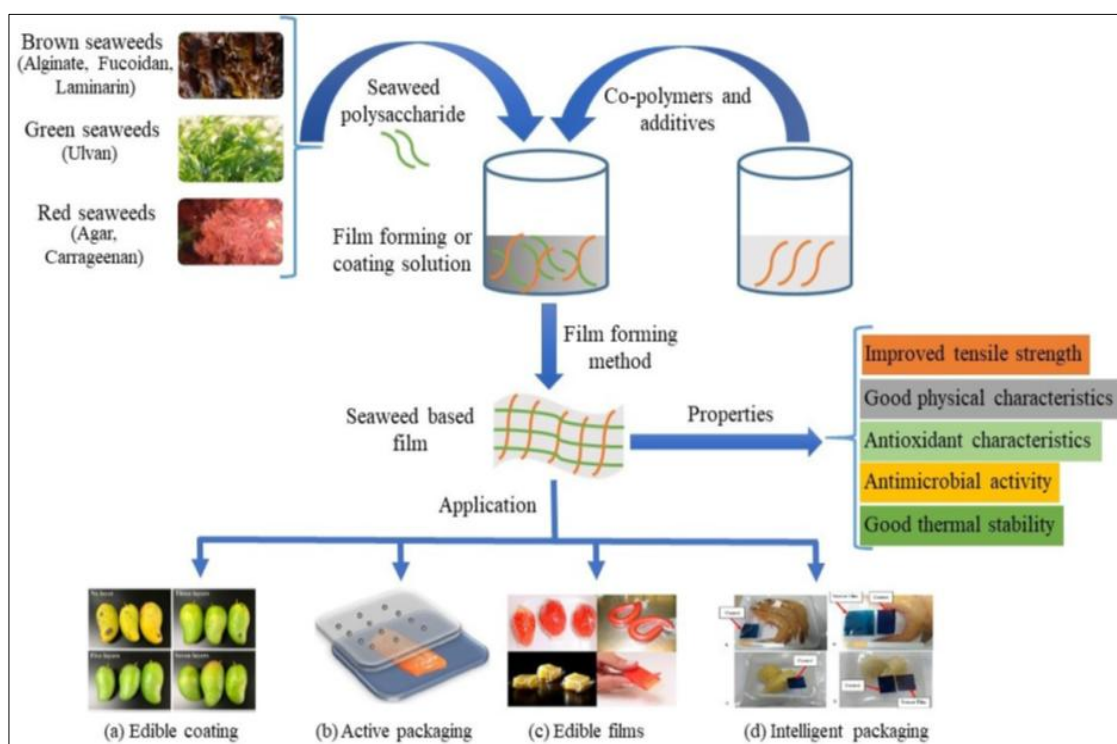
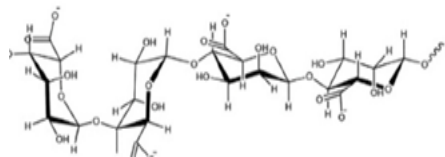
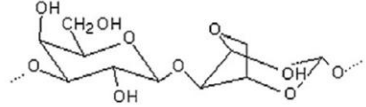
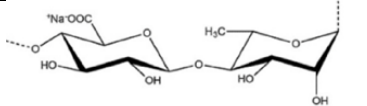


Fig 1: The mechanism for developing seaweed-based food contact materials. (a) Mangoes coated in chitosan- and alginate-based coatings enriched with cinnamon essential oil microcapsules (Yin *et al.*, 2019) ^[76], (b) Active packaging of cold-smoked salmon with Zn-MgO/Alginate film (Vizzini *et al.*, 2020) ^[71], (c) Some examples of edible films (Nešić *et al.*, 2020), (d) Intelligent packaging of shrimp and durian using ι-carrageenan based colorimetric pH sensor film (Ahmad *et al.*, 2020) ^[1]

As previously stated, the seaweeds are divided into three groups based on their pigmentation: green seaweeds (Chlorophyceae), red seaweeds (Rhodophyceae), and brown seaweeds (Phaeophyceae). Ulvan is an acidic polymer that is produced by the green seaweeds *Cladophora*, *Ulva*, and *Monostroma*. Agar and carrageenan are commonly produced by the red seaweeds *Poryphyra capensis*, *Aeodes orbitosa*, and *Notogenia stiriata*. The polysaccharides Alginate, Fucoidan, and Laminarin are produced by the brown seaweeds *Laminaria pallida*, *Fucus*, and *Zonaria* species. While brown seaweed has a high protein level, all seaweed species have a high carbohydrate content, making up over 40% of the mass (Nakhate *et al.*, 2021) ^[80]. Alginate, Agar, and Carrageenan are the seaweed polysaccharides that are most frequently utilised as FCMs

(Table 1). D-mannuronic acid and L-guluronic acid (G) in a variety of molecular weights, ratios, and topologies make up alginate. The ratio of mannuronic acid to guluronic acid determines the characteristics of alginate. Alginate has a greater capacity to establish strong bonds when it contains more guluronic acid. On the other hand, a softer and more flexible structure is created when the amounts of guluronic acid are low. Alginate has special colloidal qualities due to its chemical structure, which helps to stabilise and thicken films or coatings. Because alginate reacts effectively and permanently with divalent and trivalent metal cations to form water-insoluble polymers, it is employed as a coating material. Alginate is highly transparent and homogeneous, and it may form films well (Kocira *et al.*, 2021).

Table 1: Seaweed polysaccharides commonly used as food contact materials

Seaweed	Polysaccharide	Structure	Reference
Brown seaweeds	Alginate		Carina <i>et al.</i> , (2021) ^[15]
Red seaweeds	Agar		
Green seaweeds	Ulvan		

3. Edible coatings

According to Bourlieu *et al.*, (2008) ^[81], edible coatings are thin protective layers that are directly placed to a product's surface and can be eaten with it. According to Cerqueira *et al.*, (2010) ^[17], they are composed of natural film-formers that stick to the product's surface and form a protective layer that can help extend its shelf life by minimising or preventing natural chemical, biochemical, or microbiological degradation processes brought on by gas contact, gas diffusion, or water transfer. Adhesiveness to the product, a uniform and invisible surface appearance, neutral or favourable sensory qualities, a flawless cover, and a composition that complies with food standards are all essential characteristics of an edible coating.

4. Edible coatings for RTE sea food products

The application of edible coatings in RTE food products has a lot of potential. Although little study has been done on the application of such coatings in RTE muscle food products, Yousuf *et al.*, (2021) ^[77] have highlighted this potential. The most recent research on the application of edible coatings in RTE fish was reviewed. Studies involving edible coatings for muscle RTE goods expanded the scope of the inquiry. The characteristics of blends or multi-layer applications, as well as single materials with and without additives, are investigated. Table 1 summarises some of the major conclusions.

Table 2: Edible coatings for Ready-To-Eat fish and meat products

Product	Edible coating material and coating method	Additional packaging	Storage conditions	Source
Ready-to-eat seafood	Chitosan in acetic acid and glycerol, or alginate with no glycerol using dipping method	-	4 and 14 °C	Bremenkamp <i>et al.</i> , (2024) ^[14]
Retail maki sushi	Chitosan coating applied using spraying method	Packed under MAP conditions	4 and 8 °C	Sorbo <i>et al.</i> , (2022) ^[69]
Smoked sea bass fillets	Chitosan, alginate with glycerol, applied using dipping method	Packed under vacuum	4 °C	Martinez <i>et al.</i> , (2018) ^[55]
Cold-smoked bass fillet	Corn zein-based coating with lemongrass essential oil or nisin applied using spraying method	PVC bags with headspace or in vacuum	4 °C	Hager <i>et al.</i> , (2019) ^[36]
Cooked and peeled shrimps	Chitosan, glycerol, Tween 80 coating incorporated with 0.5% of oregano and thyme EO applied with dipping method	Packed under MAP conditions (40% CO ₂ /60% N ₂) in polystyrene trays with a PET/PVdC/PE film	4 °C	Carrion-Granda <i>et al.</i> , (2016) ^[16]

When it came to regulating the safety (microbial growth) and quality (water loss and lipid oxidation) of a Ready-to-Eat (RTE) fish product under ideal and abused storage conditions, a chitosan coating containing 1% (w/v) chitosan in 1% (v/v) acetic acid and 15% (w/w chitosan) glycerol or a 1% (w/v) alginate coating with no glycerol and no crosslinking (Bremenkamp and Sousa-Gallagher, 2024) ^[14]. With a three-fold longer shelf life than the uncoated products kept at 4°C, the chitosan-coated samples performed the best, indicating that edible coatings have a great deal of potential to improve the safety and shelf life of RTE fish products (Bremenkamp and Sousa-Gallagher, 2024) ^[14]. Additionally, the evaluated coatings showed that they may perform protective functions under abusive storage environments. A chitosan coating decreased the viable counts of mesophilic, psychophilic, and anaerobic bacteria and also delayed oxidation in smoked sea bass fillets packed

in a vacuum bag and kept at 4 °C (Martínez *et al.*, 2018) ^[55]. Although the items coated with alginate provided better protection against oxidation, the development of bacteria was not inhibited. The growth of lactic acid and psychotropic bacteria was positively inhibited by cooked and peeled prawns with a chitosan-thyme coating packed under MAP conditions in a tray with a film stored at 4°C for up to 12 days (Carrión-Granda *et al.*, 2016) ^[16]. Retail maki sushi with chitosan-coated salmon, particularly when combined with low CO₂-MAP packaging, was found to improve the microbiological stability and maintain the colorimetric characteristics of the sample stored at abused temperature conditions (8 °C). It was suggested as a suitable hurdle technology for safety precautions against temperature abuse in the food cold chain (Sørbo and Lerfall, 2022) ^[69]. Using an edible crude nano-coating solution based on carboxymethyl chitosan, a water-soluble derivative of

chitosan, and garlic aqueous extract, spiced cooked RTE chicken meat reduced the growth of microbes and slowed the rate of lipid oxidation and protein breakdown (Diao *et al.*, 2020) ^[27]. With an emphasis on the inhibition of *Listeria monocytogenes*, cold-smoked sunshine bass fillets coated with corn zein-based coating containing lemongrass essential oil or nisin and packed in bags with headspace air or vacuumed were examined. The results demonstrated that both coatings decreased the cell count in both investigated packaging systems (Hager *et al.*, 2019) ^[36]. Over the course of the 42-day testing period, it was discovered that the nisin-treated samples were the most efficient additives against *L. monocytogenes*. Additionally, it was found that samples treated with corn zein-lemongrass essential oil in bags containing headspace air were the only ones that prevented the growth of spoiling organisms. A chitosan coating on RTE meatballs was studied by Antoniadou *et al.* (2019) ^[7]. In addition to the inhibition effect on *L. monocytogenes*, other microbial populations were also counted, resulting in a shelf-life extension of about 14 days. Other studies that concentrated on controlling *L. monocytogenes* in RTE meat products confirmed a positive effect of edible coatings with or without antimicrobials to reduce or even inhibit the growth. The results of the sensory test demonstrated that the RTE meat balls' sensory qualities were unaffected by the chitosan covering. For RTE roast beef kept in cool storage, a packaging system including an edible chitosan covering devoid of additives and a synthetic polymer bag was investigated (Beverly *et al.*, 2008) ^[11]. The goal was to investigate how the coating preparation solvent solution and chitosan molecular weight affected the decrease effect against *L. monocytogenes*. When compared to lactic acid solvent, chitosan coating made with an acetic acid solution was more successful in lowering *L. monocytogenes*. Additionally, the study verified that *L. monocytogenes* on the surface of RTE roast beef products may be managed with chitosan coatings. Cold-smoked salmon was also used to investigate the anti-listerial properties of chitosan-based edible coatings combined with vacuum packaging (Jiang *et al.*, 2011) ^[43].

The population of *L. monocytogenes* on cold-smoked salmon was found to be inhibited by a chitosan coating devoid of antimicrobials during vacuum storage under refrigeration; however, tested chitosan coatings containing antimicrobials exhibited the strongest anti-listerial action. With an emphasis on *L. monocytogenes*, Jiang *et al.*, (2011) ^[43] investigated the impact of edible coatings on two RTE turkey products to regulate microbial development. In addition to several antimicrobials in single and binary combinations, various polysaccharide coatings were investigated as carrier materials. On the turkey products, alginate, kappa-carrageenan, pectin, xanthan gum, and starch showed good adhesion and stability. The product's texture, colour, scent, and general look were unaffected by the coatings that were applied. Pectin was marginally less effective than the other antimicrobial treatments, but the efficiency of the various treatments were similar throughout the studied carrier materials. Overall, it was demonstrated that, depending on the antimicrobials chosen, alginate-based coatings can enhance the safety of poached and roasted turkey by preventing the growth of *L. monocytogenes* and lowering background microbiota levels over the course of an 8-week storage period at 4 °C. Another study used vacuum packing into high barrier pouches and edible antimicrobial

coatings to prevent the growth of *L. monocytogenes* on roasted turkey (Jiang *et al.*, 2011) ^[43]. Sliced roasted turkey was used to test coatings made of starch, chitosan, alginate, and pectin with various antimicrobials throughout both cold and frozen storage. The findings shown that frozen storage may increase the efficacy of pectin-based antimicrobial edible coatings, which show promise in improving the safety of RTE poultry items. The investigated polysaccharide-based carrier coatings containing antimicrobials exhibited anti-listerial efficacy in the following order: pectin, alginate, chitosan, and starch.

Edible coatings for RTE fish items, including fried prawns, smoked fish bass, smoked salmon and retail maki sushi, were studied in these experiments. Roast beef, fried meat balls, cooked chicken breast, and cooked turkey meat were the RTE meat products under investigation. The main focus was on edible coatings based on chitosan, either with or without antibacterial additives. Furthermore, as antimicrobial carrier coatings, corn-zein, pectin, alginate, starch, gelatine, kappa-carrageenan, and xanthan gum were investigated. The suppression of microbial growth, with a focus on *L. monocytogenes*, a prevalent foodborne pathogen in RTE meals, was the primary goal of the edible coating investigations. It was demonstrated that adding a coating protection layer to the food product's surface enhanced existing packaging techniques such high barrier synthetic films, pouches, or trays, extending the safety and quality of RTE items. In addition to being a viable fresh-keeping technique for RTE items (Diao *et al.*, 2020) ^[27], edible coating techniques may also be an appropriate barrier technology for safety precautions against temperature abuse in the food cold chain (Sørbrø and Lerfall, 2022) ^[69]. In addition to microbial destruction, only a small number of research examined other protective characteristics such fat oxidation or water loss (Martínez *et al.*, 2018) ^[55]. In the case of RTE food goods, little research has been done on how an edible coating might safeguard food products' physical, biological, or chemical quality alterations while serving a variety of packaging purposes. The potential application of a coating as an integrated component of a packaging system can be increased by managing certain degradation processes. It was observed that the tested edible coatings were not designed to replace the functions of the current packaging system, but rather as an additional layer of protection for the core container. Further research is necessary to determine whether an edible coating and an outer layer work well together as an eco-packaging design alternative. It was also observed that only composite coatings containing antimicrobials and a polysaccharide carrier substance were investigated. RTE seafood items were not used to test other possible techniques, such as blends or multilayer coatings, to enhance coating performance (López-Caballero *et al.*, 2005) ^[53].

5. Seaweeds application as food contact materials

5.1 Active packaging

In order to prolong shelf life, increase safety, and improve sensory qualities while maintaining product quality, active packaging is a novel technique that can be defined as a type of packaging in which the package, the product, and the environment interact. According to European regulation (EC) No 450/2009, active packaging refers to packaging systems that interact with food in a way that "deliberately contains components that would release or absorb

substances into or from the packed food or the environment surrounding the food." The active packaging approach integrates existing food packaging concepts with the preservation qualities of antimicrobials and other substances. Food-derived chemicals are either absorbed by the packaging around the food or discharged into the food or the environment. Active packaging systems come in two varieties: active-releasing systems (emitters) and active-scavenging systems (absorbers). The emitters add substances to packed food or the headspace, such as antimicrobial compounds, flavours, ethylene, carbon dioxide, antioxidants, or ethanol, while the absorber eliminates unwanted molecules from food or its surroundings, such as moisture, carbon dioxide, oxygen, ethylene, or odour (Biji *et al.*, 2015) ^[13].

The amount of active compounds like antioxidants and antimicrobials required may be decreased by using active packaging rather than directly adding them to the food. The majority of fresh and processed foods have microbial growth or meal degradation on their surfaces. Therefore, it is customary to add active compounds to the majority of the diet. Additionally, when active compounds are introduced directly to food, their activity may be decreased or inhibited due to interactions with food ingredients and/or during food processing. Therefore, it might be more effective to add active substances through active packaging rather than adding them to the food's bulk. Moisture control packaging, oxygen scavengers, carbon dioxide generating systems,

antimicrobial active packaging, ethylene scavengers, and flavour and odour absorbent packaging are only a few of the several active food packaging systems currently under development (Sharma *et al.*, 2020) ^[67].

The most popular kind of active packaging is Oxygen Scavengers (OS), which function by taking oxygen out of the surrounding air and stopping it from reacting with the product. One way to preserve food in an oxygen-free environment is through vacuum packaging (Rao and Sachindra, 2002). Another technology for eliminating oxygen from the headspace of food packing is Modified Atmosphere Packaging (MAP), which modifies the packaging environment. MAP is a more flexible method than vacuum packing, which mainly concentrates on eliminating oxygen from the headspace (Dey and Neogi, 2019) ^[26]. Additional oxygen scavenging packaging techniques include systems based on iron, platinum group metals, unsaturated hydrocarbons, tocopherol, ascorbic acid, enzymes, and microorganisms. Nevertheless, it has been discovered that MAP or vacuum packaging can lower the potentially hazardous residual oxygen content in the headspace to just 0.5-2 vol%. Conversely, oxygen scavengers can reduce oxygen levels to less than 0.1 vol% percent, extending the shelf life (Mills *et al.*, 2005) ^[57]. As shown in Figure 2, Andrade *et al.*, (2021) ^[5] created an active covering of whey protein concentrate and *Fucus vesiculosus* extract to prevent chicken breasts from oxidising their lipids.

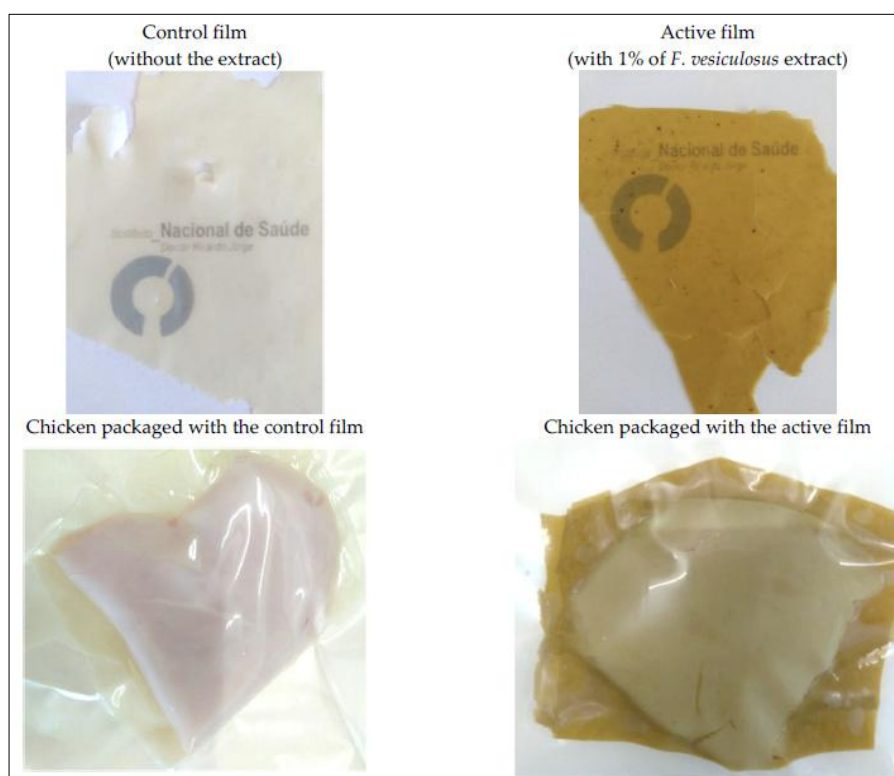


Fig 2: Whey protein control film and active film with 1% *Fucus vesiculosus* (brown seaweed) extract (Source: Andrade *et al.*, 2021) ^[5]

Table 3: Recent application of seaweed polysaccharides in active and intelligent packaging

Packaging matrix	Active component	Properties of the packaging material	Reference
Sodium alginate	Lemongrass oil	- Controlled release of lemon grass oil due to microencapsulation - Films were able to inhibit growth of <i>E. coli</i> and <i>L. monocytogenes</i>	Bustos <i>et al.</i> , (2016)
Furcellaran	Gelatin hydrolysate/ Rosemary extract	- Increased thickness, water content, and tensile strength - Colour changes in different pH were observed - High antioxidant activity	Jancikova <i>et al.</i> , (2010)

Sodium alginate	Carboxymethyl cellulose, CaCl ₂ , Pyrogalllic acid	- Higher elongation at break - Increased moisture content, water vapor permeability, and oxygen permeability - Effective against <i>E. coli</i> and <i>S. aureus</i>	Han and Wang (2017)
<i>Gelidium sesquipedale</i>	Polyvinyl alcohol, Nanocellulose	Enhanced properties for the incorporation and release of bioactive extracts	De Oliveira <i>et al.</i> , (2019)
<i>Fucus vesiculosus</i>	Whey protein	- Strengthened the thickness, tensile strength, and elastic modulus - Inhibit lipid oxidation of packaged poultry meat, at least for 25 days of storage	Han and Wang (2017)

5.2 Smart and intelligent packaging

During transit, storage, retail sales, and use, intelligent packaging monitors a product's quality, safety, and location. The European Food Safety Authority (EFSA) defines intelligent packaging materials as "items and materials that monitor the state of packaged food or the environment surrounding the food" (2009). They do not interact with the packaged product, but they may transfer its conditions (Biji *et al.*, 2015) ^[13]. The future of food packaging, according to experts, will be the next generation of intelligent packaging. The perception of packaging has undergone yet another significant change as a result of intelligent packaging technologies, which convert conventional packaging communication functions into intelligent communication. According to Barska and Wyrwa (2017) ^[9], there are two most popular kinds of intelligent packaging. While the second directly evaluates the product's quality inside the packaging and may come into direct contact with food, requiring additional food safety and quality controls, the first is based on assessing elements outside the packaging (Dainelli, *et al.*, 2008) ^[24]. As shown in Table 3, the three fundamental technologies used in intelligent packaging systems are typically data carriers, indications, and sensors (Ghaani *et al.*, 2016) ^[33].

5.2.1 Data carriers

Data carriers facilitate the efficient flow of information across the supply chain. Data carriers are used to defend against theft, imitation, automation, and traceability (Muller and Schmid, 2019) ^[59]. To guarantee this, data carriers transmit and store information on distribution, storage, and other aspects. They are therefore commonly found on tertiary packaging. The most popular data carriers are RFID (Radio Frequency Identification) tags and barcode labels (Ghaani *et al.*, 2016) ^[33].

5.2.2 Indicators

A material's presence or absence, the degree of a substance's interaction with other compounds, or the concentration of a particular substance are all detected by indicators. This information is visualised through direct modifications, like different colour intensities (Ahmed *et al.*, 2018) ^[2]. According to the indicator, they are placed either inside or outside the package (Muller and Schmid, 2019) ^[59]. Time-temperature indicators, freshness indicators, and leakage indicators are the most common forms of intelligent packaging available. According to their purpose, the indicators are divided into three categories: time-Temperature Integrators or Indicators (TTI), Critical Temperature Indicators (CTI), and Critical Temperature/Time Integrators (CTTI) (Barska and Wyrwa, 2017) ^[9].

5.2.3 Sensors

According to Lee *et al.*, (2015) ^[50], a sensor is a device that uses a signal to detect or measure a physical or chemical property in order to identify, quantify, or detect energy or matter. A sensor and a receptor are the two components that make up most sensors. It is possible to identify some chemical or physical analytes by measuring their presence, activity, composition, or concentration. Additionally, the receptor transforms chemical or physical information into an energy form that the transducer, the second unit, can detect (Mlalila *et al.*, 2016) ^[58]. Furthermore, the measured signal is transformed into an analytical signal that may be used by the transducer. It is possible to employ a thermal, chemical, optical, or electrical signal (Kerry *et al.*, 2006) ^[48]. Gas sensors, chemical sensors, and biosensors are a few examples of the several kinds of sensors that track different attributes.

6. Effects of seaweeds on food contact materials

6.1 Mechanical properties

The quality of polymer films appropriate for food packaging is determined by mechanical factors like tensile strength, elastic modulus, and elongation at break. These measures demonstrate the film's ability to withstand a variety of stresses that arise during the handling, preparation, and storage of packaged food without losing its integrity. The connections and solubility of the chemicals as well as the intermolecular interactions between polymer chains largely dictate the mechanical properties of composite films made by the blending process. Furthermore, rather than only hydrogen interactions with water molecules, the presence of integrated chemicals may cause structural changes in the film matrix, leading to a less dense structure that may allow for enhanced interaction between components. Numerous research have also examined the effect of seaweed polysaccharide addition on mechanical quality. More than half of the examined studies showed an increase in tensile strength when seaweed polysaccharides were included into the matching polymer. Food packaging films with superior mechanical qualities were created using alginate and starch (Maizura *et al.*, 2007) ^[54]. Alginate-based films and other agar/starch-based films exhibit superior mechanical properties (Wu *et al.*, 2009) ^[72]. Huq *et al.*, (2012) ^[39] used solution casting to create a nanocrystalline cellulose reinforced alginate-based nanocomposite film. According to the study, the tensile strength of the nanocomposite reinforced with 5 weight percent nanocrystalline cellulose content is 37% higher than that of the control. But Goonoo *et al.* (2017) ^[34] have also created a polysaccharide content blend that includes polyhydroxybutyrate-co-valerate and fucoidan. At 27 °C, 60% relative humidity, and a crosshead speed of 10 mm/min, the tensile strength was measured. There was an increase in flexibility and a drop in tensile

modulus for the Fucooidan/Polyhydroxybutyrate-co-valerate combination.

6.2 Physical properties

It is challenging to predict morphological changes after the addition of elements like seaweed polysaccharides since they heavily rely on the interaction between the polymer and the seaweed. However, the integration of several compounds could lead to gaps and other modifications that could impact engineering properties in the future, therefore they are worth researching. It has been shown that the monomer sequence affects the physical characteristics of alginates. The most important physical characteristics of alginates are the preferential binding of multivalent cations, which forms the basis for gel formation, and the fact that the sol/gel transition of alginates is independent of temperature (Draget and Taylor, 2011) [29]. Using Scanning Electron Microscopy (SEM), Jumaidin *et al.*, (2016) [44] created an agar film with varying amounts of sugar palm starch and examined the surface morphology. According to the study, the SEM picture showed a smooth, uniform surface with no sugar palm starch phases or clusters after adding Agar to the mixture, suggesting that the two film components are miscible and interact well. However, breaking structures emerged on the surface as the Agar concentration rose, which may have been caused by a higher filler content in the film matrix and polymer-polymer bonding. Lopes *et al.*, (2017) [52] used SEM analysis of Polyhydroxy butyrate film samples to examine the morphological alterations brought about by the addition of esterified alginate to the Polyhydroxy butyrate blend. The Polyhydroxy butyrate blend's morphological structure changed with the addition of the polysaccharide, showing a thick, rough, and open surface texture. Eghbalifam *et al.*, (2015) [31] created a poly vinyl alcohol/sodium alginate film and examined the films' surface morphology. The SEM image analysis revealed that the blend film had a homogenous texture, indicating high miscibility and no phase separation.

6.3 Chemical properties

The safety and effectiveness of FCMs are mostly determined by chemical properties like hydrophilicity or hydrophobicity as well as the makeup of a film including functional groups in FCM (Carina *et al.*, 2021) [15]. The static contact angle of gelatin and sodium caseinate films combined with brown seaweed *Ascophyllum nodosum* (*A. nodosum*) extract was measured in a study by Kadam *et al.*, (2021) [45] using the sessile drop technique. The contact angle decreased when seaweed extract was added. When more seaweed extract was added, the hydrophilicity of both films increased. Furthermore, the inclusion of seaweed extract greatly boosted the polar component of the surface free energy. The seaweed extract's high hydroxyl group content increased the polar component of surface free energy, which in turn increased the films' hydrophilicity. In a different study, the addition of Grapefruit Seed Extract (GSE) significantly affected the hydrophobicity of composite films based on carrageenan. The Water Contact Angle (WCA) of the control carrageenan film was greater than that of the Carrageenan/GSE composite film. Because GSE is hydrophilic, the WCA of the composite films decreased dramatically as the concentration of GSE increased (Kanmani and Rhim, 2014) [46].

6.4 Thermal properties

The changes in material properties throughout the heating process can be ascertained with the aid of thermal analysis techniques (Wang *et al.*, 2016, Assadpour *et al.*, 2020) [82, 83]. The thermal profiles of polymers and their composites are frequently examined using the Thermogravimetry Analysis (TGA) and Differential Scanning Calorimetry (DSC) techniques (Jafarzadeh & Jafari, 2020) [84]. The difference in the amount of heat required to raise the temperature of the material and the reference as a function of temperature and time is measured using DSC (Garavand *et al.*, 2017) [32]. Thermal properties such as glass transition temperature (T_g), melting temperature (T_m), and crystallization temperature (T_c) can be determined from a DSC measurement (Jafarzadeh and Jafari, 2020) [84]. The endothermic peak specific energy values (170.9-197.1 J/g) of chitosan-based edible films including seaweeds (FH, FP) and seaweed extracts (FHE, FPE) were greater in DSC analysis than those of chitosan-only films (<100 J/g). Thus, the addition of seaweeds enhances both the films' ability to absorb water and the interactions between the polymer and water. Furthermore, the addition of seaweed had no effect on the T_g of the edible films. Nevertheless, the T_g of chitosan films was not adversely affected by the inclusion of seaweed. DSC investigation of gelatin films containing *A. nodosum* extract revealed two distinctive transitions between 53.6 and 58.9 °C and 124.3 and 132.3 °C in another study. The first transition was not greatly affected by the use of seaweed extract. On the other hand, with the addition of seaweed, a significant rise in the transition temperature was seen for the second transition. After seaweed was added, the non-disulfide covalent bond may have increased the stability of the film network, raising the films' transition temperature. Furthermore, the inclusion of *A. nodosum* extract significantly decreased the T_g of the sodium caseinate films; this could be because the low-molecular-weight components of the seaweed extract have a plasticising effect (Kadam *et al.*, 2015) [45].

6.5 Antimicrobial properties

One crucial feature of FCMs that can be utilised to increase food safety is their antimicrobial qualities. Antimicrobial qualities enable the growth of microbes to be blocked or decreased, preventing food deterioration, decreasing food waste, and extending the food product's shelf life (Carina *et al.*, 2021) [15]. The chemical components that give seaweeds their antibacterial properties include proteins, fatty acids, carbohydrates, and phenols. Fucooidan demonstrated antimicrobial activity against *E. coli*, *S. aureus*, *P. aeruginosa*, *A. hydrophila* (Alboofetileh *et al.*, 2019) [3], and Sargassum, while essential oil extracted from *Undaria Pinnatifida* demonstrated antimicrobial activity against *S. aureus* and *S. Typhimurium* (Patra *et al.*, 2017) [64]. According to Chakraborty *et al.*, (2017) [18], Myriocystum shown antibacterial efficacy against *Vibrio parahaemolyticus*, *Vibrio*, and *A. hydrophila*. When added to polyvinyl alcohol, *Kappaphycus alvarezii* red seaweed extract maintained its antibacterial efficacy against *S. aureus* and *B. cereus* (Kanatt *et al.*, 2015) [85]. The use of these crude seaweed extracts as antibacterial agents in food packaging has not received much research. However, the seaweed polysaccharide has no discernible antibacterial activity, according to certain studies. *Salmonella enterica* and *Klebsiella pneumonia* were not susceptible to the antibacterial action of the sodium alginate-ferulic acid film

(Yerramathi *et al.*, 2021) ^[75]. To boost the antibacterial action of seaweeds, essential oils, plant extracts, or nanoparticles have been added. *S. aureus* was completely inhibited by the Carrageenan-Starch film combined with Carvacrol, whereas the film containing Carvacrol exhibited no antibacterial activity. Additionally, olive leaf extract was added to the carrageenan-based packing material to suppress psychrophile bacterial growth up to five times during the preservation of lamb meat (Martiny *et al.*, 2020) ^[56]. By adding zinc oxide nanorods to cellulose that was separated from the green seaweed *Ulva fasciata*, Bhutiya *et al.* (2018) ^[12] produced an active food packaging material. Both gram-positive (*S. aureus*, *B. cereus*, *S. thermophilis*) and gram-negative (*E. coli*, *P. aeruginosus*) bacteria were susceptible to the antimicrobial activity of this packing material.

6.6 Antioxidant properties

Food contact materials' antioxidant qualities are essential for lowering protein deterioration and lipid oxidation in packaged foods. Food products' quality, nutritional content, shelf life, and attractiveness are all significantly impacted by lipid oxidation. One of the main causes of food spoilage, which leads to a significant quantity of food waste, is lipid oxidation. Antioxidants are therefore added to films and coatings during active packaging, increasing the materials' antioxidant qualities (Carina *et al.*, 2021) ^[15]. In addition to gradually migrating to the food product's surface during storage, these integrated antioxidant agents can reduce the issues related to lipid oxidation. Antioxidant qualities are present in the majority of seaweeds utilised as FCMs. For instance, Kanatt *et al.*, (2015) ^[85] studied the bioactive properties of *Kappaphycus alvarezii*, red seaweed, and this film exhibited good antioxidant activity when measured by the DPPH (2,2-diphenyl-1-picrylhydrazyl) assay. Up to 25 days of storage, the addition of *Fucus vesiculosus* seaweed extract to a Whey protein film enhanced the antioxidant potential and prevented lipid oxidation in the chicken breast (Andrade *et al.*, 2021) ^[5]. However, the use of essential oils and plant extracts that can lessen the food product's lipid oxidation strengthens the materials' antioxidant qualities. The antioxidant activity of the gelatin-sodium alginate film was enhanced by the addition of tea polyphenols (Dou *et al.*, 2018) ^[28]. Ferulic acid increased the antioxidant capacity of a sodium alginate edible film many times. Carrageenan films with different concentrations of olive leaf extract were also studied. The films' antioxidant qualities grow as the amount of olive leaf extract increases (Da Rosa *et al.*, 2020) ^[23].

7. Coating application methods

The product surface can be coated with biobased materials by vacuum impregnation, spraying, or dipping. Please see Senturk Parreidt *et al.* (2018) ^[63] and Andriani & Handayani (2023) ^[6] for more specific details. The biopolymer must be dissolved in a solvent in order to prepare the initial coating formulation. This must be followed by component addition, homogenisation, and a degassing step (filter, ultra-bath, centrifugation, or resting). Other procedures, such as heating, may be required to guarantee structural breakdown or enhance dissolving capabilities, depending on the coating ingredients. The most popular coating technique in laboratories is dipping (Senturk Parreidt *et al.*, 2018) ^[63]. After dipping the product into a coating formulation for a predetermined amount of time, excess solution is drained out, and the solvent is evaporated to dry the product. To

guarantee a continuous film formation on the product's surface, the coating procedure is usually repeated using the same or a different solution. Products with intricate and uneven surfaces can be evenly coated by dipping. The viscosity of the coating formulation allows for some control over the coating thickness (Cisneros-Zevallos and Krochta, 2003) ^[21]. However, coatings applied by dipping are typically thicker than those applied by spraying (Senturk Parreidt *et al.*, 2018) ^[63]. Coating hydrophilic product surfaces with a hydrophobic coating solution may present challenges. By encouraging the physical and chemical bonding of oppositely charged materials, a layer-by-layer coating technique can resolve this problem (Andriani & Handayani, 2023) ^[6]. The possibility of cross-contamination when several items are dipped in the same coating solution, which could cause product components to dissolve into the coating solution, is one disadvantage of the dipping procedure.

Spraying is a coating technique in which a nozzle is used to disperse the coating solution as droplets over the desired food surface area. This technique has a number of benefits, including the ability to manage the solution's temperature, producing a homogeneous coating with a controllable thickness, requiring less coating solution because of the high spraying pressure, and being appropriate for multilayer applications. Working with a wider product surface area is also made possible by this method's avoidance of coating solution contamination. The characteristics of the coating solution (density, viscosity, and surface tension), the operating conditions (flow rate, air pressure, etc.), and the system settings (nozzle design, spray angle, etc.) all have an impact on the coating effectiveness of the spraying system. It is crucial to take into account the coating solution's spray-flowing properties, where a low viscosity is ideal. However, a problem may arise since many biobased polymers have a high viscosity at low polymer concentrations. It is feasible to combine the dipping and spraying techniques, which offers benefits including a thinner layer, improved coverage, and regulated thickness (Amanatidou *et al.*, 2000) ^[4].

A third coating technique that uses the same dipping and draining procedures as the dipping method is vacuum impregnation. To guarantee quick and direct migration of the coating material into the samples' porous tissues, vacuum impregnation involves coating the samples in a vacuum chamber. The process involves extracting liquids and gases from the product's pores and substituting them with coating solutions while atmospheric pressure is restored (Zhao *et al.*, 2019) ^[78]. To guarantee full coating coverage surrounding the product, samples were frequently left to dry after the coating application before being further packed or stored. There have been reports of drying at room temperature, in cold storage, or at higher temperatures with turbulent or laminar air movement. There are very few studies on edible coatings for RTE seafood or comparable products that use vacuum impregnation or spraying; the majority of studies use the dipping method. To close the gap between research and practical applications, more study of the spraying techniques is advised.

8. Coating performance measurement methods

Adhesiveness, water and gas barriers, antibacterial and antioxidant capabilities, appearance, taste, and feel are all significant coating characteristics. This section's goal is to give a summary of the approaches utilised to verify and

contrast coating performances. According to Bourlieu *et al.*, (2008) ^[81] and López-Caballero *et al.*, (2005) ^[53], the viscoelastic properties of the coating formulations such as pH value, elastic modulus, viscosity modulus, solubility, phase angle as a function of temperature, and electrical charge are crucial for guaranteeing simple handling and application and boosting industrial feasibility.

The adhesiveness, coating thickness, and coating integrity characteristics are important when the coating is applied to the product. The type of material and the quantity of contacts or bonds between the coating and support determine how adhesive the coating material is on the product (Comaposada *et al.*, 2018) ^[22]. By measuring the product of interest's contact angle both before and after coating, some researchers examined coating adhesiveness (Cerqueira *et al.*, 2010) ^[17]. Additionally, imaging analysis can be used to assess the coating's penetration and surface integrity. A Scanning Electron Microscope (SEM) can be used to measure the coating thickness.

Relevant details regarding the coating's performance can be found in its barrier qualities against gas and water. The barrier characteristics of dry-cast films (permeability) or the barrier measures of the coating immediately applied to the product (resistance) are used to assess the barrier efficacy of coating materials. However, because food contact can have a significant impact on the barrier qualities of the coating material applied to the product, assessing the barrier qualities of casted coating films has the drawback that it is frequently challenging to extrapolate the results (Guo *et al.*, 2014) ^[35]. When comparing the performance of various coatings, factors such as water activity, relative humidity, water loss rate, surface area, saturation pressure, and storage temperature are taken into account. The rate of water loss (g/h) or the water vapour resistance of the coating (s/cm) are measured to assess the relative water loss of coated products (Ben-Yehoshua *et al.*, 1985) ^[10]. This approach has been used for a variety of coatings and food products, despite the fact that research on the impact of barrier qualities on edible coatings with the product is still restricted. This technique makes it possible to evaluate the effectiveness of various coating materials on a range of products. Measuring the gas exchange rates (such as O₂ or CO₂) of the coated product with the headspace volume in a closed system is another straightforward way to investigate the gas barrier of a coating (Cerqueira *et al.*, 2010) ^[17].

Microbial, chemical, and physical investigations can be used to evaluate how the coating affects food sample deterioration. The growth of bacteria, yeast, and mould can be measured to assess antimicrobial qualities; the particular strains used depend on the food product and storage conditions of interest. Water loss, water activity, nitrogen degradation, and fat oxidation (peroxide value, malondialdehyde value, total volatile basic nitrogen, or trimethylamine-nitrogen), as well as pH variations and adenosine triphosphate breakdown during storage, can all be measured to track physical-chemical deterioration (Socaciu *et al.*, 2018) ^[68]. A colorimeter can be used to analyse changes in the product's appearance, and a texture analyser can evaluate the coated and non-coated goods' hardness, elasticity, cohesiveness, adhesiveness, chewiness, and gumminess (López-Caballero *et al.*, 2005) ^[53]. The look, smell, texture, firmness, colour, taste, juiciness, and flavour

of coated goods can all be studied through sensory evaluations. The literature has employed a variety of techniques to assess coating performance (Andriani and Handdayani, 2023) ^[6]. However, there are still no established techniques for assessing the barrier, penetration, and integrity of the coating. Furthermore, because the coating qualities are greatly influenced by the product or interactive properties, it is difficult to compare coatings applied to various food products. Indirect measurements are still widely used in coating investigations, and there are few direct methods for examining the coating qualities.

9. Current trends and future prospects of the utilization of seaweeds for edible coatings

Seaweeds have emerged as one of the most promising renewable resources for the development of edible coatings due to their biodegradability, abundance, non-toxicity, and excellent film-forming properties. Recent research has focused on seaweed-derived polysaccharides such as alginate, agar, carrageenan, fucoidan, laminarin, and ulvan, which serve as natural coating materials for fruits, vegetables, seafood, meat products, and ready-to-eat foods. These polysaccharides provide effective barriers against moisture loss, oxygen transmission, and microbial contamination, thereby extending shelf life and maintaining food quality. Seaweed-based coatings are increasingly being combined with natural bioactive compounds, including antioxidants, antimicrobial agents, essential oils, and plant extracts, to create active edible coatings with enhanced preservation capabilities. A major current trend is the incorporation of seaweed extracts rich in phenolic compounds, pigments, and antioxidants into edible coatings. These bioactive components improve oxidative stability and inhibit microbial growth while enhancing the nutritional value of foods. Another important development is the use of green extraction technologies, such as Pressurized Liquid Extraction (PLE), ultrasound-assisted extraction, and supercritical fluid extraction, which enable the sustainable recovery of valuable compounds from seaweeds. Furthermore, seaweed polysaccharides are being integrated with nanoparticles, proteins, and other biopolymers to improve mechanical strength, water resistance, and functional performance. Industrial applications have also expanded, with seaweed-based edible films and coatings already being commercialized for packaging and food preservation. Future prospects for seaweed-based edible coatings are highly promising. Advances in nanotechnology, smart packaging, and active coating systems are expected to produce multifunctional coatings capable of monitoring food freshness while simultaneously extending shelf life. The development of customized coatings tailored to specific food products and storage conditions will further enhance their commercial value. Increased consumer demand for sustainable, plastic-free packaging solutions and stricter environmental regulations are likely to accelerate the adoption of seaweed-derived coatings. However, challenges such as large-scale production, cost reduction, standardization of raw materials, and optimization of barrier properties must be addressed. Overall, seaweed-based edible coatings represent a sustainable and innovative technology with significant potential to replace synthetic packaging materials and contribute to a greener and more efficient food preservation industry.

10. Conclusion

Seaweeds represent a valuable and sustainable source of biopolymers for the development of edible biofilms and coatings with significant potential in modern food packaging systems. The presence of naturally occurring polysaccharides such as alginate, agar, carrageenan, fucoidan, laminarin, and ulvan provides excellent film-forming, gelling, thickening, and stabilizing properties that support the production of biodegradable food contact materials. Seaweed-based coatings effectively reduce moisture loss, lipid oxidation, microbial growth, and quality deterioration, thereby enhancing food safety and extending the shelf life of a wide range of products, including fruits, vegetables, seafood, meat products, and ready-to-eat foods. Research findings demonstrate that the incorporation of natural antioxidants, antimicrobial agents, plant extracts, essential oils, and nanoparticles significantly improves the mechanical strength, thermal stability, barrier performance, and functional properties of seaweed-derived coatings. In addition to serving as edible protective layers, these materials have shown considerable promise in active and intelligent packaging applications capable of monitoring food freshness and quality during storage and distribution. Their biodegradability, renewability, and compatibility with food systems make them attractive alternatives to conventional petroleum-based packaging materials. Despite these advantages, several challenges continue to limit large-scale industrial adoption. Variability in seaweed composition, high production costs, limited cultivation capacity, scalability issues, and the need for improved water resistance and mechanical properties require further investigation. Future research should focus on advanced extraction technologies, nanotechnology-assisted formulations, multilayer coating systems, and smart packaging innovations to enhance functionality and commercial feasibility. Overall, seaweed-based edible biofilms offer a promising pathway toward environmentally friendly, sustainable, and high-performance food packaging solutions that can contribute significantly to reducing plastic waste while ensuring food quality, safety, and shelf-life extension.

Acknowledgment: The authors are grateful to the authorities of college of fisheries and department of fish processing technology or providing facilities to conduct their research.

Funding: The authors didn't receive any financial assistance during the conduction of research.

Conflicts of interest: The authors declare that there are no conflicts of interest.

References

- Ahmad NA, Heng LY, Salam F, Zaid MHM, Hanifah SA. A colorimetric pH sensor based on *Clitoria* sp and *Brassica* sp for monitoring of food spoilage using chromametry. *Sensors* (Basel). 2019;19(21):4813. DOI:10.3390/s19214813.
- Ahmed I, Lin H, Zou L, Li Z, Brody AL, Qazi IM, *et al.* An overview of smart packaging technologies for monitoring safety and quality of meat and meat products. *Packag Technol Sci.* 2018;31(7):449-471. DOI:10.1002/pts.2380.
- Alboofetileh M, Rezaei M, Tabarsa M, Rittà M, Donalisio M, Mariatti F, *et al.* Effect of different non-conventional extraction methods on the antibacterial and antiviral activity of fucoidans extracted from *Nizamuddinina zanardinii*. *Int J Biol Macromol.* 2019;124:131-137. DOI:10.1016/j.ijbiomac.2018.11.201.
- Amanatidou A, Slump R, Gorris L, Smid EJ. High oxygen and high carbon dioxide modified atmospheres for shelf-life extension of minimally processed carrots. *J Food Sci.* 2000;65(1):61-66. DOI:10.1111/j.1365-2621.2000.tb15956.x.
- Andrade MA, Barbosa CH, Souza VGL, Coelho IM, Reboleira J, Bernardino S, *et al.* Novel active food packaging films based on whey protein incorporated with seaweed extract: development, characterization, and application in fresh poultry meat. *Coatings.* 2021;11(2):229. DOI:10.3390/coatings11020229.
- Andriani V, Handayani NA. Recent technology of edible coating production: A review. *Mater Today Proc.* 2023;87:200-206. DOI:10.1016/j.matpr.2023.02.397.
- Antoniadou D, Govaris A, Ambrosiadis I, Sergelidis D. Effect of chitosan coating on the shelf life of ready-to-eat bovine meatballs and the control of *Listeria monocytogenes* growth on their surface during refrigeration storage. *J Hellenic Vet Med Soc.* 2019;70(2):1495. DOI:10.12681/jhvms.20820.
- European Food Safety Authority. Guidelines on submission of a dossier for safety evaluation by the EFSA of active or intelligent substances present in active and intelligent materials and articles intended to come into contact with food. *EFSA J.* 2009;7(8):1208. DOI:10.2903/j.efsa.2009.1208.
- Barska A, Wyrwa J. Innovations in the food packaging market-intelligent packaging-a review. *Czech J Food Sci.* 2017;35(1):1-6. DOI:10.17221/268/2016-CJFS.
- Ben-Yehoshua S, Burg SP, Young R. Resistance of citrus fruit to mass transport of water vapor and other gases. *Plant Physiol.* 1985;79(4):1048-1053. DOI:10.1104/pp.79.4.1048.
- Beverly RL, Janes ME, Prinyawiwatkula W, No HK. Edible chitosan films on ready-to-eat roast beef for the control of *Listeria monocytogenes*. *Food Microbiol.* 2008;25(3):534-537. DOI:10.1016/j.fm.2007.11.002.
- Bhutiya PL, Mahajan MS, Rasheed MA, Pandey M, Hasan SZ, Misra N. Zinc oxide nanorod clusters deposited seaweed cellulose sheet for antimicrobial activity. *Int J Biol Macromol.* 2018;112:1264-1271. DOI:10.1016/j.ijbiomac.2018.02.108.
- Biji KB, Ravishankar CN, Mohan CO, Gopal TKS. Smart packaging systems for food applications: a review. *J Food Sci Technol.* 2015;52(10):6125-6135. DOI:10.1007/s13197-015-1766-7.
- Bremenkamp I, Sousa-Gallagher MJ. Design and development of an edible coating for a ready-to-eat fish product. *Polymers* (Basel). 2024;16(3):346. DOI:10.3390/polym16030346.
- Carina D, Sharma S, Jaiswal AK, Jaiswal S. Seaweeds polysaccharides in active food packaging: a review of recent progress. *Trends Food Sci Technol.* 2021;110:559-572. DOI:10.1016/j.tifs.2021.02.022.
- Carrión-Granda X, Fernández-Pan I, Jaime I, Rovira J, Maté JI. Improvement of the microbiological quality of ready-to-eat peeled shrimps (*Penaeus vannamei*) by the use of chitosan coatings. *Int J Food Microbiol.*

- 2016;232:144-149.
DOI:10.1016/j.ijfoodmicro.2016.05.029.
17. Cerqueira MA, Sousa-Gallagher MJ, Macedo I, Rodriguez-Aguilera R, Souza BW, Teixeira JA, *et al.* Use of galactomannan edible coating application and storage temperature for prolonging shelf-life of "Regional" cheese. *J Food Eng.* 2010;97(1):87-94. DOI:10.1016/j.jfoodeng.2009.09.019.
 18. Chakraborty K, Thilakan B, Chakraborty RD, Raola VK, Joy M. O-heterocyclic derivatives with antibacterial properties from marine bacterium *Bacillus subtilis* associated with seaweed, *Sargassum myriocystum*. *Appl Microbiol Biotechnol.* 2017;101(2):569-583. DOI:10.1007/s00253-016-7810-3.
 19. Chang C, Lin F, Tsai S, Gavahian M, Cheng K, Hou C, *et al.* Active packaging incorporating chitosan, casein phosphopeptide, and plasmonic modification to maintain quality and regulate the respiration rate of fresh-cut *Pyrus serotina* Rehder during storage. *Food Packag Shelf Life.* 2023;40:101223. DOI:10.1016/j.fpsl.2023.101223.
 20. Characterization of nanoencapsulated food ingredients. In: Elsevier eBooks. 2020. doi:10.1016/C2017-0-03547-4.
 21. Cisneros-Zevallos L, Krochta J. Dependence of coating thickness on viscosity of coating solution applied to fruits and vegetables by dipping method. *J Food Sci.* 2003;68(2):503-510. DOI:10.1111/j.1365-2621.2003.tb05702.x.
 22. Comaposada J, Marcos B, Bou R, Gou P. Influence of surfactants and proteins on the properties of wet edible calcium alginate meat coatings. *Food Res Int.* 2018;108:539-550. DOI:10.1016/j.foodres.2018.04.002.
 23. Da Rosa GS, Vanga SK, Garipey Y, Raghavan V. Development of biodegradable films with improved antioxidant properties based on the addition of carrageenan containing olive leaf extract for food packaging applications. *J Polym Environ.* 2020;28(1):123-130. DOI:10.1007/s10924-019-01589-7.
 24. Dainelli D, Gontard N, Spyropoulos D, Beuken E, Tobback P. Active and intelligent food packaging: legal aspects and safety concerns. *Trends Food Sci Technol.* 2008;19:S103-S112. DOI:10.1016/j.tifs.2008.09.011.
 25. De Oliveira JP, Bruni GP, Fabra MJ, Da Rosa Zavareze E, López-Rubio A, Martínez-Sanz M. Development of food packaging bioactive aerogels through the valorization of *Gelidium sesquipedale* seaweed. *Food Hydrocoll.* 2019;89:337-350. DOI:10.1016/j.foodhyd.2018.10.047.
 26. Dey A, Neogi S. Oxygen scavengers for food packaging applications: a review. *Trends Food Sci Technol.* 2019;90:26-34. DOI:10.1016/j.tifs.2019.05.013.
 27. Diao X, Huan Y, Chitrakar B. Extending the shelf life of ready-to-eat spiced chicken meat: garlic aqueous extracts-carboxymethyl chitosan ultrasonicated coating solution. *Food Bioprocess Technol.* 2020;13(5):786-796. DOI:10.1007/s11947-020-02428-7.
 28. Dou L, Li B, Zhang K, Chu X, Hou H. Physical properties and antioxidant activity of gelatin-sodium alginate edible films with tea polyphenols. *Int J Biol Macromol.* 2018;118(Pt B):1377-1383. DOI:10.1016/j.ijbiomac.2018.06.121.
 29. Draget KI, Taylor C. Chemical, physical and biological properties of alginates and their biomedical implications. *Food Hydrocoll.* 2011;25(2):251-256. DOI:10.1016/j.foodhyd.2009.10.007.
 30. Drago E, Campardelli R, Barbucci A, Perego P. Polycaprolactone sub-micrometric fibers optimization for primary packaging loaded with fatty acids as natural phase change materials. *J Food Eng.* 2023;358:111680. DOI:10.1016/j.jfoodeng.2023.111680.
 31. Eghbalifam N, Frounchi M, Dadbin S. Antibacterial silver nanoparticles in polyvinyl alcohol/sodium alginate blend produced by gamma irradiation. *Int J Biol Macromol.* 2015;80:170-176. DOI:10.1016/j.ijbiomac.2015.06.042.
 32. Garavand F, Rouhi M, Razavi SH, Cacciotti I, Mohammadi R. Improving the integrity of natural biopolymer films used in food packaging by crosslinking approach: a review. *Int J Biol Macromol.* 2017;104(Pt A):687-707. DOI:10.1016/j.ijbiomac.2017.06.093.
 33. Ghaani M, Cozzolino CA, Castelli G, Farris S. An overview of the intelligent packaging technologies in the food sector. *Trends Food Sci Technol.* 2016;51:1-11. DOI:10.1016/j.tifs.2016.02.008.
 34. Goonoo N, Bhaw-Luximon A, Passanha P, Esteves S, Schönherr H, Jhurry D. Biomineralization potential and cellular response of PHB and PHBV blends with natural anionic polysaccharides. *Mater Sci Eng C Mater Biol Appl.* 2017;76:13-24. DOI:10.1016/j.msec.2017.02.156.
 35. Guo M, Jin TZ, Wang L, Scullen OJ, Sommers CH. Antimicrobial films and coatings for inactivation of *Listeria innocua* on ready-to-eat deli turkey meat. *Food Control.* 2014;40:64-70. DOI:10.1016/j.foodcont.2013.11.018.
 36. Hager JV, Rawles SD, Xiong YL, Newman MC, Thompson KR, Webster CD. *Listeria monocytogenes* is inhibited on fillets of cold-smoked sunshine bass, *Morone chrysops* × *Morone saxatilis*, with an edible corn zein-based coating incorporated with lemongrass essential oil or nisin. *J World Aquac Soc.* 2019;50(3):575-592. DOI:10.1111/jwas.12573.
 37. Han Y, Wang L. Sodium alginate/carboxymethyl cellulose films containing pyrogalllic acid: physical and antibacterial properties. *J Sci Food Agric.* 2017;97(4):1295-1301. DOI:10.1002/jsfa.7863.
 38. Haridevamuthu B, Raj D, Chandran A, Murugan R, Seetharaman S, Dhanaraj M, *et al.* Sustainable food packaging: harnessing biowaste of *Terminalia catappa* L. for chitosan-based biodegradable active films for shrimp storage. *Carbohydr Polym.* 2024;329:121798. DOI:10.1016/j.carbpol.2024.121798.
 39. Huq T, Salmieri S, Khan A, Khan RA, Tien CL, Riedl B, *et al.* Nanocrystalline cellulose (NCC) reinforced alginate based biodegradable nanocomposite film. *Carbohydr Polym.* 2012;90(4):1757-1763. DOI:10.1016/j.carbpol.2012.07.065.
 40. Irimia A, Grigoraş VC, Popescu C. Active cellulose-based food packaging and its use on foodstuff. *Polymers (Basel).* 2024;16(3):389. DOI:10.3390/polym16030389.

41. Jafarzadeh S, Jafari SM. Impact of metal nanoparticles on the mechanical, barrier, optical and thermal properties of biodegradable food packaging materials. *Crit Rev Food Sci Nutr*. 2021;61(16):2640-2658. DOI:10.1080/10408398.2020.1783200.
42. Jancikova S, Jamróz E, Kulawik P, Tkaczewska J, Dordevic D. Furcellaran/gelatin hydrolysate/rosemary extract composite films as active and intelligent packaging materials. *Int J Biol Macromol*. 2019;131:19-28. DOI:10.1016/j.ijbiomac.2019.03.050.
43. Jiang Z, Neetoo H, Chen H. Control of *Listeria monocytogenes* on cold-smoked salmon using chitosan-based antimicrobial coatings and films. *J Food Sci*. 2011;76(1):M22-M26. DOI:10.1111/j.1750-3841.2010.01925.x.
44. Jumaidin R, Sapuan S, Jawaid M, Ishak, Sahari J. Characteristics of thermoplastic sugar palm starch/agar blend: thermal, tensile, and physical properties. *Int J Biol Macromol*. 2016;89:575-581. DOI:10.1016/j.ijbiomac.2016.05.028.
45. Kadam SU, Pankaj S, Tiwari BK, Cullen P, O'Donnell CP. Development of biopolymer-based gelatin and casein films incorporating brown seaweed *Ascophyllum nodosum* extract. *Food Packag Shelf Life*. 2015;6:68-74. DOI:10.1016/j.fpsl.2015.09.003.
46. Kanmani P, Rhim J. Development and characterization of carrageenan/grapefruit seed extract composite films for active packaging. *Int J Biol Macromol*. 2014;68:258-266. DOI:10.1016/j.ijbiomac.2014.05.011.
47. Kaur J, Singh J, Rasane P, Gupta P, Kaur S, Sharma N, *et al*. Natural additives as active components in edible films and coatings. *Food Biosci*. 2023;53:102689. DOI:10.1016/j.fbio.2023.102689.
48. Kerry J, O'Grady M, Hogan S. Past, current and potential utilisation of active and intelligent packaging systems for meat and muscle-based products: a review. *Meat Sci*. 2006;74(1):113-130. DOI:10.1016/j.meatsci.2006.04.024.
49. Kocira A, Kozłowicz K, Panasiewicz K, Staniak M, Szpunar-Krok E, Hortyńska P. Polysaccharides as edible films and coatings: characteristics and influence on fruit and vegetable quality-a review. *Agronomy*. 2021;11(5):813. DOI:10.3390/agronomy11050813.
50. Lee SY, Lee SJ, Choi DS, Hur SJ. Current topics in active and intelligent food packaging for preservation of fresh foods. *J Sci Food Agric*. 2015;95(14):2799-2810. DOI:10.1002/jsfa.7218.
51. Lima DAS, Grisi CVB, Florentino GIB, Santos MMF, Madruga MS, Da Silva FAP. Preparation and characterization of sustainable active packaging based on myofibrillar proteins and protein hydrolysates from the cutting by-product of *Scomberomorus brasiliensis* filleting on the band saw machine. *Food Chem*. 2024;460(Pt 1):140490. DOI:10.1016/j.foodchem.2024.140490.
52. Lopes JR, Reis RAD, Almeida LE. Production and characterization of films containing poly(hydroxybutyrate) (PHB) blended with esterified alginate (ALG-e) and poly(ethylene glycol) (PEG). *J Appl Polym Sci*. 2017;134(1):44362. DOI:10.1002/app.44362.
53. López-Caballero M, Gómez-Guillén M, Pérez-Mateos M, Montero P. A chitosan-gelatin blend as a coating for fish patties. *Food Hydrocoll*. 2005;19(2):303-311. DOI:10.1016/j.foodhyd.2004.06.006.
54. Maizura M, Fazilah A, Norziah M, Karim A. Antibacterial activity and mechanical properties of partially hydrolyzed sago starch-alginate edible film containing lemongrass oil. *J Food Sci*. 2007;72(6):C324-C330. DOI:10.1111/j.1750-3841.2007.00427.x.
55. Martínez O, Salmerón J, Epelde L, Vicente M, De Vega C. Quality enhancement of smoked sea bass (*Dicentrarchus labrax*) fillets by adding resveratrol and coating with chitosan and alginate edible films. *Food Control*. 2018;85:168-176. DOI:10.1016/j.foodcont.2017.10.003.
56. Martiny TR, Raghavan V, De Moraes CC, Da Rosa GS, Dotto GL. Bio-based active packaging: carrageenan film with olive leaf extract for lamb meat preservation. *Foods*. 2020;9(12):1759. DOI:10.3390/foods9121759.
57. Mills A, Doyle G, Peiro AM, Durrant J. Demonstration of a novel, flexible, photocatalytic oxygen-scavenging polymer film. *J Photochem Photobiol A Chem*. 2005;177(2-3):328-331. DOI:10.1016/j.jphotochem.2005.06.001.
58. Mlalila N, Kadam DM, Swai H, Hilonga A. Transformation of food packaging from passive to innovative via nanotechnology: concepts and critiques. *J Food Sci Technol*. 2016;53(9):3395-3407. DOI:10.1007/s13197-016-2325-6.
59. Müller P, Schmid M. Intelligent packaging in the food sector: A brief overview. *Foods*. 2019;8(1):16. DOI:10.3390/foods8010016.
60. Nasution H, Harahap H, Julianti E, Safitri A, Jaafar M. Smart packaging based on polylactic acid: the effects of antibacterial and antioxidant agents from natural extracts on physical-mechanical properties, colony reduction, perishable food shelf life, and future prospective. *Polymers (Basel)*. 2023;15(20):4103. DOI:10.3390/polym15204103.
61. Nasution H, Harahap H, Julianti E, Safitri A, Jaafar M. Properties of active packaging of PLA-PCL film integrated with chitosan as an antibacterial agent and *Syzygium cumini* seed extract as an antioxidant agent. *Heliyon*. 2024;10(1):e23952. DOI:10.1016/j.heliyon.2023.e23952.
62. Nešić A, Cabrera-Barjas G, Dimitrijević-Branković S, Davidović S, Radovanović N, Delattre C. Prospect of polysaccharide-based materials as advanced food packaging. *Molecules*. 2020;25(1):135. DOI:10.3390/molecules25010135.
63. Parreidt TS, Müller K, Schmid M. Alginate-based edible films and coatings for food packaging applications. *Foods*. 2018;7(10):170. DOI:10.3390/foods7100170.
64. Patra JK, Lee S, Park JG, Baek K. Antioxidant and antibacterial properties of essential oil extracted from an edible seaweed *Undaria pinnatifida*. *J Food Biochem*. 2017;41(1):e12278. DOI:10.1111/jfbc.12278.
65. Rao DN, Sachindra NM. Modified atmosphere and vacuum packaging of meat and poultry products. *Food Rev Int*. 2002;18(4):263-293. DOI:10.1081/FRI-120016206.
66. Ristivojević P, Jovanović V, Opsenica DM, Park J, Rollinger JM, Velicković TC. Rapid analytical approach for bioprofiling compounds with radical

- scavenging and antimicrobial activities from seaweeds. *Food Chem.* 2020;334:127562. DOI:10.1016/j.foodchem.2020.127562.
67. Sharma R, Jafari SM, Sharma S. Antimicrobial bio-nanocomposites and their potential applications in food packaging. *Food Control.* 2020;112:107086. DOI:10.1016/j.foodcont.2020.107086.
 68. Socaciu M, Semeniuc CA, Vodnar DC. Edible films and coatings for fresh fish packaging: focus on quality changes and shelf-life extension. *Coatings.* 2018;8(10):366. DOI:10.3390/coatings8100366.
 69. Sørbo S, Lerfall J. Effect of edible coating and modified atmosphere packaging on the microbiological and physicochemical stability of retail maki sushi. *J Food Sci.* 2022;87(3):1211-1229. DOI:10.1111/1750-3841.16065.
 70. Stanley J, John A, Črešnar KP, Zemljč LF, Lambropoulou DA, Bikiaris DN. Active agents incorporated in polymeric substrates to enhance antibacterial and antioxidant properties in food packaging applications. *Macromol.* 2022;3(1):1-27. DOI:10.3390/macromol3010001.
 71. Vizzini P, Beltrame E, Zanet V, Vidic J, Manzano M. Development and evaluation of qPCR detection method and Zn-MgO/alginate active packaging for controlling *Listeria monocytogenes* contamination in cold-smoked salmon. *Foods.* 2020;9(10):1353. DOI:10.3390/foods9101353.
 72. Wu Y, Geng F, Chang PR, Yu J, Ma X. Effect of agar on the microstructure and performance of potato starch film. *Carbohydr Polym.* 2009;76(2):299-304. DOI:10.1016/j.carbpol.2008.10.031.
 73. Xing Y, Gong X, Wang P, Wang Y, Wang L. Occurrence and release of organophosphite antioxidants and novel organophosphate esters from plastic food packaging. *J Agric Food Chem.* 2023;71(30):11599-11606. DOI:10.1021/acs.jafc.3c01138.
 74. Yang Z, Zhang D, Cai J. Robust design of starch composite nanofibrous films for active food packaging: towards improved mechanical, antioxidant, and antibacterial properties. *Int J Biol Macromol.* 2024;260(Pt 1):129329. DOI:10.1016/j.ijbiomac.2024.129329.
 75. Yerramathi BB, Kola M, Muniraj BA, Aluru R, Thirumanyam M, Zyryanov GV. Structural studies and bioactivity of sodium alginate edible films fabricated through ferulic acid crosslinking mechanism. *J Food Eng.* 2021;301:110566. DOI:10.1016/j.jfoodeng.2021.110566.
 76. Yin C, Huang C, Wang J, Liu Y, Lu P, Huang L. Effect of chitosan- and alginate-based coatings enriched with cinnamon essential oil microcapsules to improve the postharvest quality of mangoes. *Materials (Basel).* 2019;12(13):2039. DOI:10.3390/ma12132039.
 77. Yousuf B, Sun Y, Wu S. Lipid and lipid-containing composite edible coatings and films. *Food Rev Int.* 2022;38(Suppl 1):574-597. DOI:10.1080/87559129.2021.1876084.
 78. Zhao X, Zhou Y, Zhao L, Chen L, He Y, Yang H. Vacuum impregnation of fish gelatin combined with grape seed extract inhibits protein oxidation and degradation of chilled tilapia fillets. *Food Chem.* 2019;294:316-325. DOI:10.1016/j.foodchem.2019.05.054.
 79. Gengatharan A, Abd Rahim MH. The application of clove extracts as a potential functional component in active food packaging materials and model food systems: a mini-review. *Appl Food Res.* 2023;3(1):100283. DOI:10.1016/j.afres.2023.100283.
 80. Nakhate P, van der Meer Y. A systematic review on seaweed functionality: a sustainable bio-based material. *Sustainability.* 2021;13(11):6174. DOI:10.3390/su13116174.
 81. Bourlieu C, Guillard V, Vallès-Pamiès B, Gontard N. Edible moisture barriers for food product stabilization. In: Aguilera JM, Lillford PJ, editors. *Food Materials Science.* New York: Springer; 2008. p. 547-575. DOI:10.1007/978-0-387-71947-4_23.
 82. Wang S, Zhang X, Wang S, Copeland L. Changes of multi-scale structure during mimicked DSC heating reveal the nature of starch gelatinization. *Sci Rep.* 2016;6:28271. DOI:10.1038/srep28271.
 83. Assadpour E, Jafari SM. Characterization of nanoencapsulated food ingredients. In: Gharanjig H, Jafari SM, editors. *Characterization of Nanoencapsulated Food Ingredients.* Academic Press; 2020.
 84. Jafarzadeh S, Jafari SM. Impact of metal nanoparticles on the mechanical, barrier, optical and thermal properties of biodegradable food packaging materials. *Crit Rev Food Sci Nutr.* 2021;61(16):2640-2658. DOI:10.1080/10408398.2020.1783200.
 85. Kanatt SR, Lahare P, Chawla SP, Sharma A. *Kappaphycus alvarezii*: Its antioxidant potential and use in bioactive packaging films. *J Microbiol Biotechnol Food Sci.* 2015;5(1):1-6. DOI:10.15414/jmbfs.2015.5.1.1-6.