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Potential of different seaweed extract compounds for sustainable post-harvest management of plant foods: A review

Mehul Chudasama[1], Asifa Khan[1] and Jyotirmoy Goyary[1*]

[1] *Department of Dairy and Food Technology Parul Institute of Technology, Parul University, Vadodara, Gujarat, India*

[*] *Corresponding author: mehulchudasama255@gmail.com*

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Abstract - Seaweeds are a rich source of various bioactive compounds with promising applications in agriculture. This article explores the extraction techniques and potential of seaweed extracts as a natural approach to post-harvest preservation of fruits and vegetables. The presence and functions of key phytohormones in seaweed i.e., auxins, cytokinin, gibberellins, and abscisic acid were explained. These hormones play a crucial role in plant growth, development, and stress responses. The article highlights how seaweed extracts containing these phytohormones can influence shelf life, quality, and disease resistance in fruits and vegetables. Studies have shown that seaweed extracts can extend shelf life by reducing weight loss, maintaining firmness, and improving nutritional content. Additionally, seaweed extracts demonstrate potential as a natural alternative to synthetic fungicides for controlling post-harvest diseases. Overall, this review suggested that seaweed extracts offer a sustainable and effective approach to enhancing the postharvest management of fruits and vegetables.

Keywords: Seaweed extract, phytohormones, ulvan, fucoidan, postharvest

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1. Introduction

Fresh fruits, a vital part of our daily diet, are unfortunately susceptible to a variety of postharvest diseases. These diseases are predominantly caused by pathogenic fungi, which are associated with decay. The impact of these fungi is particularly noticeable during the storage and transportation phases. They greatly decrease the shelf life of fresh agricultural commodities, resulting in a loss of quality and nutrients. Furthermore, these fungi are capable of producing mycotoxins, which further diminish the market value of these commodities. Historically, the primary agent used to manage these postharvest diseases has been synthetic fungicides. However, there is a growing global trend towards limiting the use of these synthetic fungicides. This shift is driven by a desire to substitute them with alternative methods, such as bio fungicides. Reducing the usage of hazardous chemical pesticides is essential as we move toward more environmentally friendly farming methods that also better safeguard human health. Although chemical control methods often provide superior protection against crop pathogen diseases, their efficacy gradually decreases. The pathogenic populations' capability to rapidly become more resistant to these substances is the cause of this. Researchers are looking for novel sources of bioactive chemicals that can control fungal diseases as a result of this severe global issue. Ideally, these novel substances are unlikely to be harmful and should have few adverse effects. The aquatic environment and its inhabitants are a significant source for unique active natural products. These metabolites are still understudied due to their diverse structures and functional characteristics. Seaweeds are major marine algae which distinguish themselves apart among other marine species. They have evolved to survive for harsh environments and have developed chemical barriers to protect themselves against adverse conditions and dangers, such as microbial infections. The secondary metabolites of seaweeds are distinct from those of terrestrial plants in their initial structures. Because of their complicated living environment, these structures developed by many metabolic pathways. Seaweeds can also yield large amounts of biomass and are independent of freshwater and agricultural land. This makes them a possible source of bioactive compounds for preventing postharvest diseases in fresh fruits. Therefore, the investigation of these marine resources may open the door to more productive and sustainable agricultural practices.

According to recent findings, marine macroalgae are abundant in naturally occurring bioactive compounds that exhibit a broad range of therapeutic potential, including antioxidant, antiviral, antifungal, antibacterial, and anticancer effects. A growing number of studies have focused on their potent antifungal action, non-phytotoxicity, systemic effect, and biodegradability with respect to crop treatments and postharvest disease management. Seaweeds have a wide range of chemical compositions, which may fluctuate according on the species, growth conditions, harvest time, growth environment, and external factors. They include a number of bioactive compounds, including polysaccharides, phlorotannin, pigments, and peptides. These chemicals have a variety of therapeutic actions, including antioxidant, anti-inflammatory, antibacterial, antiviral, and anticancer properties (Pereira & Valado, 2023).

2. Unique polysaccharides in seaweed and their role in food preservation

Seaweeds are rich in unique polysaccharides such as ulvan, fucoidan, agar, alginate, agarose, and carrageenan. These polysaccharides have been widely used as functional ingredients in the food sector due to their impressive functionalities. Some of the important compounds of different seaweed species are presented in Table 1 and different techniques for the extraction of compounds are presented in Figure 1 and Table 2.

2.1 Ulvan

Ulvan, extracted from green seaweed, has gelling properties and can be used as an antimicrobial agent in food preservation. Ulvan is a sulfated heteropolysaccharide found in the cell wall of green seaweeds, particularly the *Ulva* species (Li et al., 2023). Hot-water extraction, sometimes referred to as a maceration treatment, is usually used in the extraction process at high temperatures of 80 to 90 °C. This is followed by an ethanolic precipitation (Barakat et al., 2022). High-Performance Liquid Chromatography (HPLC), Fourier Transform Infrared Spectroscopy (FT-IR), and Nuclear Magnetic Resonance (NMR) techniques were used to determine the structure of ulvan. It has been found to have gelling properties. Because the polysaccharide contains regular sequences of aldobiuronic acid backbones and ionic species, it can form gels in aqueous metal ion solutions (e.g. 0.1 M NaCl). When ulvan was dissolved in acidic pH, it showed as dispersed beads, while at pH 13 in tetrabutyl ammonium hydroxide (TBAOH) or NaOH, it produced an open gel-like structure or a continuous film via fusion or coalescence of bead-like structures (Li et al., 2023). The food industry has found ulvan to be a viable substitute for synthetic preservatives when it comes to nisin, a type of antibacterial agent. When used against Gram-positive bacteria, ulvan particles coated with nisin demonstrated antimicrobial activity that was nearly comparable with free nisin. As a result, the food sector may use these developed complexes as bio preservatives (Kidgell et al., 2019).

Table 1. Different seaweed species and their applications

Seaweed species	Colour	Compound	Application in food processing preservation	Property	References
Wakame (*Undaria pinnatifida*)	Green-brown	Alginic acid	Thickener, gelling agent in soups, noodles, and tofu	High concentration of fucoidan, a potential anti-cancer compound	Yamanaka and Akiyama (1993)
Kombu (*Saccharina japonica*)	Dark brown	Glutamic acid (Umami)	Flavour enhancer in broths, soups, and sauces	Contains a high amount of dietary fibre	Chan et al. (2023)
Nori (*Porphyra tenera*)	Red-purple	Porphyran	Wrappings for sushi rolls	Rich in vitamins A, B, and C	Venkatra-man and Mehta (2018)
Hijiki (*Hijikia fusiforme*)	Dark brown	Fucoidan	Thickener, texturizer in vegetarian products	Contains high levels of calcium and iron	Meinita et al. (2021)
Dulse (*Palmaria palmata*)	Reddish-purple	Carrageenan	Thickener, stabilizer in dairy products, condiments	Can grow in a wide range of water tem-peratures	Mouritsen et al. (2013)
Irish Moss (*Chondrus crispus*)	Reddish-purple	Carrageenan	Gelling agent in puddings, ice cream	Traditionally used as a cough suppressant	Flynn et al. (2018)
Kelp (*Laminaria digitata*)	Brown	Alginic acid	Thickener, stabilizer in processed meats, beverages	Can grow to giant sizes, reaching up to 50 meters	Ratcliff et al. (2017)
Arame (*Eisenia bicyclis*)	Dark brown	Alginic acid	Thickener, gelling agent in salads, noodles	Known for its slightly sweet and nutty flavour	Tahanzadeh et al. (2022)
Wakame (*Undaria pinnatifida*)	Green-brown	Fucoxanthin	Natural food colouring in beverages, snacks	May have anti-obesity properties	Yoshinaga and Mitamura (2019)
Sea Lettuce (*U. lactuca*)	Green	Ulvan	Thickener, emulsifier in vegan mayonnaise, dressings	High in protein and omega-3 fatty acids	Sefrienda et al. (2023)
Eucheuma cottonii	Red	Carrageenan	Thickener, stabilizer in jams, jellies	Can be farmed sustainably, making it a reliable source	Matanjun et al. (2008)
Hizikia fusiforme (Young)	Light brown	Fucoidan	Thickener, texturizer in vegetarian burgers	High in chlorophyll, potentially reducing inflammation	Jia et al. (2020)
Sargassum horneri	Yellow-brown	Fucoidan	Thickener, emulsifier in salad dressings	Can tolerate harsh weather conditions	Balboa et al. (2022)
Codium fragile	Green	Dietary fibre	Prevents syneresis (liquid separation) in yogurt	Known for its unique, finger-like appearance	Kim et al. (2020)

Table 1. Different seaweed species and their applications (cont.)

Seaweed species	Colour	Compound	Application in food processing preservation	Property	References
Gracilaria vermiculophylla	Red	Agar-agar	Gelling agent in vegetarian jellies, confectionery	Contains high levels of gel-forming polysaccharides	Lee et al. (2022)
Gelidium amansii	Red	Agar-agar	Thickener, stabilizer in Asian desserts	Can be harvested multiple times in a year	Zhang et al. (2024)
Cladosiphon okamuranus (Mung Bean Seaweed)	Green	Dietary fibre, vitamins	Thickener, bulking agent in noodles, soups	Traditionally used as a digestive aid in Asian cultures	Nishitsuji et al. (2020)
Enteromorpha compressa	Light green	Ulvan	Thickener, stabilizer in processed meats	High in minerals, including iron, iodine, and magnesium	Mamatha et al. (2007)
Ecklonia cava	Brown	Phlorotannin	Antioxidant in processed foods, nutraceuticals	May have beneficial effects on blood sugar control	Li et al. (2023)
Caulerpa lentillifera (Green Caviar)	Light green	Ulvan	Texturizer, gelling agent in vegan caviar substitutes	Often used for its luxurious texture and visual appeal	Syakilla et al. (2023)
Spirulina (*Arthrospira platensis*)	Blue-green	Phycocyanin	Natural colouring agent in beverages, snacks	High in complete protein, all essential amino acids	Kadam and Dhanipkar (2022)
Haematococcus pluvialis (Astaxanthin Algae)	Red	Astaxanthin	Natural colouring agent in salmon, trout (aquaculture)	Potent antioxidant, may improve skin health	Li et al. (2023)
Jania rubens (Coralline Algae)	Pink/Red	Calcium carbonate	Mineral supplement in fortified foods, beverages	Contributes to healthy bones and teeth	Chenniyappan et al. (2019)
Liagora tetrasporifera (Sea Beans)	Green	Dietary fibre, minerals	Thickener, texturizer in vegetarian meatballs	Known for its crunchy texture and slightly salty flavour	Lin et al. (2011)
Porphyra umbilicalis (Lavochia)	Red-purple	Porphyran	Wrappings for Korean gimbap (seaweed rice rolls)	High in vitamins and minerals, including vitamin B12	Venkatraman and Mehta (2018)
Sargassum filiforme	Brown	Fucoidan	Thickener, emulsifier in plant-based milks	Can be a fast-growing and readily available resource	Balboa et al. (2022)
Undaria pinnatifida (Sporophyll)	Green-brown	Fucoxanthin	Natural colouring agent in noodles, pasta	May have benefits for heart health and weight management	Lee et al. (2023)

Table 1. Different seaweed species and their applications (cont.)

Seaweed species	Colour	Compound	Application in food processing preservation	Property	References
G. chilensis	Red	Agar-agar	Gelling agent in laboratory cultures, microbial growth	Agarose, derived from agar-agar, is used in gel electrophoresis	Lee et al. (2022)
P. palmata (Dulse)	Light green	Dietary fibre, minerals	Thickener, flavour enhancer in breads, crackers	Traditionally used as a natural remedy for coughs and colds	Lopes et al. (2019)
Codium fragile	Light green	Dietary fibre, minerals	Thickener, stabilizer in dips, spreads	Can be a good source of dietary fibre and antioxidants	Jang et al. (2024)

2.2 Fucoidan

Brown algae contain the sulfated polysaccharide fucoidan. Numerous enveloped viruses have been shown to be prevented from replicating when exposed to it. It can improve fruit quality preservation and reduce loss during mango postharvest storage (Luthuli et al., 2019). Various types of brown algae contain fucoidan, a long-chain sulfated polysaccharide. It has a complicated molecular structure with various degrees of acetylation and sulfation (Li et al., 2008). The word fucoidan comes from fucose, which is the primary sugar present in the polymer backbone. Fucose is frequently accompanied by other sugars such as galactose, xylose, arabinose, and rhamnose (Li et al., 2008). Seaweed plant cells contain fucoidan, which acts as a barrier against external forces. It has been discovered that the same defensive qualities that are valuable to the seaweed plant can also be beneficial to human and animal health (Li et al., 2008). Potential therapeutic benefits of fucoidan include its ability to inhibit the growth of cancer cells and exhibit anti-inflammatory and anticoagulant qualities. Numerous enveloped viruses have been observed to be prevented from replicating when exposed to it (Wang et al., 2021; Lin et al., 2020; Luthuli et al., 2019). In terms of handling fruits and vegetables after harvest, fucoidan has demonstrated promising results. When cucumbers were kept in cold storage, fucoidan treatment reduced the risk of chilling injury, prevented weight loss, decreased respiration rate and electrolyte leakage, and delayed the formation of malondialdehyde. In cucumbers under cold stress, fucoidan treatment preserved the integrity of the cell membrane (Zhang et al., 2023). It can also reduce the loss of mango during postharvest storage and better maintain fruit quality (Chen et al., 2022). The application of fucoidan to strawberries enhances their resistance to cold by preventing the breakdown of total polyphenol and ascorbic acid and preventing the reduction of their antioxidant capacity (Duan et al., 2019). After being treated with fucoidan, cucumbers have been shown to have improved cold resistance during cold storage by preserving energy metabolism and successfully increasing antioxidant capacity (Zhang et al., 2023). Fucoidan extraction technique and seaweed species used to extract fucoidan are major factors in determining the bioactivity of fucoidan extracts. A wide range of factors affect fucoidan production, including source seaweed species, global regulatory approvals, purity, bioactivity, and extraction processes (Li et al., 2008).

2.3 Agar

Agar is a hydrocolloid extracted from certain species of red algae, primarily from the genera *G. Gelidium,* and *Pterocladia* (Sinurat et al., 2023). It is a polymer composed of galactose subunits. Agarose and agaropectin are its two main components. About 70% of the mixture is composed of agarose. It is the component that forms gels and is a linear polysaccharide. The branching, non-gelling part of agar is called agaropectin (Bhavsar et al., 2019). The transparent, amorphous substance known as agar is separated from the algae and produced as bricks, flakes, or powder. Agar cannot be dissolved in cold water, although it can absorb up to 20 times its own weight. When added to hot water, it dissolves easily; a diluted solution remains liquid at 42 °C but becomes a stiff gel at 37 °C (Pandya et al., 2022). It possesses a distinctive characteristic called hysteresis, which is the variation in its melting and gelation temperatures, together with a high gelling strength. Essentially, this means that unless an agar gel is heated to a temperature much higher than its setting point, it will not melt (Pandya et al., 2022). Agar offers a stable substrate for the growth of bacteria at temperatures that are similar to those of the human body, making this property particularly useful in the field of microbiology (Al-blooshi et al., 2021).

2.4 Alginate

Alginic acid is another name for alginate. It is a polymer that occurs naturally in brown algae. When hydrated, this hydrophilic substance transforms into a viscous gum. Alkaline extraction is the main method used to extract alginate. Seaweed is submerged in a solution containing 2.5% sodium carbonate and 1% formaldehyde to make sodium alginate. A brown seaweed species called *Sargassum wightii* has been shown to have a yield of 31.7% sodium alginate, which is a relatively high yield (Jayasinghe et al., 2022). Edible films and coatings made of alginate have drawn attention due to their ability to increase and preserve food quality while extending its shelf life. They function by lowering respiration, regulating dehydration, increasing mechanical qualities, and improving product appearance. These films may be used on a range of food products, such as cheese, fruits, vegetables, meats, chicken and seafood (Parreidt et al., 2018). When exposed to calcium ions (Ca 2+), alginate forms a gel matrix. This property is helpful for making films made of alginate. These films provide short-term defense against food water loss when utilised as packaging (Castro-Yobal et al., 2021).

2.5 Carrageenan

A class of naturally occurring linear sulfated polysaccharides known as carrageenan is derived from red, edible seaweeds. Its thickening, stabilizing, and gelling capabilities make it a popular ingredient in the food industry. As an anionic polysaccharide, carrageenan comprises 15-40% ester-sulfate content. (Hossain et al., 2024). Carrageenan are classified into three types based on their sulphate content:

kappa-carrageenan has one sulphate group per disaccharide, iota-carrageenan has two, and lambda-carrageenan has three (Mokhtari et al., 2021). Carrageenan derives primarily from specific varieties of red seaweed that are members of the Rhodophyta division. Seaweeds belonging to the genera *Chondrus, Gigartina, Eucheuma,* and *Kappaphycus* are frequently used in the synthesis of carrageenan derivatives. The most popular source of kappa-carrageenan is *K. alvarezii,* which is mostly cultivated in Asian countries including Indonesia, the Philippines, Vietnam, and Malaysia (Rupert et al., 2022). Carrageenan is a high molecular weight linear polysaccharide comprising repeating galactose units and 3,6-anhydrogalactose (3,6 AG), both sulphated and non-sulphated, joined by alternating α- (1,3) and β- (1,4) glycosidic links (Mokhtari et al., 2021). The large, extremely flexible molecules that comprise the chemical structure of the various carrageenan species create curling helical forms. As a result, they can produce a wide range of gels at ambient temperature. They are frequently utilised as thickening and stabilising agents in the food industry as well as other sectors (Mokhtari et al., 2021). Since carrageenan is found in seaweed naturally, the process of manufacture mostly involves extracting it from the seaweed. Following harvest, the seaweed is baled, dried, and shipped to the company which manufactures carrageenan. After being pulverized and properly cleaned, the seaweed undergoes screening in order to remove any impurities like sand. Centrifugation and filtering are used to separate the cellulose from the carrageenan following treatment with a hot alkali solution (5-8% potassium hydroxide) (Hossain et al., 2024). Carrageenan is a multipurpose ingredient that is extracted from aquatic harvested red algae. It is widely used in culinary categories such as meat, jelly, ice cream, and puddings as a thickening, stabilizer, and gelling agent. It is designated as food additive E407 and E407a (with cellulose content) in Europe. It is typically natural, safe, kosher, halal, vegan, and gluten-free (Hossain et al., 2024). As a polymer electrolyte with low manufacturing costs, accessibility, affordability, minimal environmental impact, eco-sustainable nature, and biocompatibility, carrageenan biopolymers show great promise as biopolymer materials for the use of energy resources (Yermak et al., 1999). Additionally, carrageenan-derived biopolymers are now produced at a level suitable for meeting the large-scale demands of a variety of sectors (Yermak et al., 1999). Ismail et al. (2023) examined *Polycladia myrica, Sirophysalis trinodis, Dictyota spiralis, S. euryphyllum,* and *Turbinaria decurrens,* five brown seaweed species. Each seaweed species exhibited significant levels of phlorotannin, with P. myrica having the highest concentration.

3. Different polyphenols in seaweed

Seaweeds that produce phenolic compounds include *Ascophyllum nodosum*, *Bifurcaria bifurcata*, *Fucus vesiculosus*, *Leathesia marina*, *Lobophora variegata*, *Macrocystis pyrifera*, *Asparagopsis armata*, *Chondrus crispus*, *Gracilaria* sp., *K. alvarezii*, *Neopyropia* sp., *P. palmata*, *Dasycladus vermicularis*, *Derbesia tenuissima*, and *U. intestinalis* (Gonçalves, 2021). Because phenolic compounds are naturally bioactive and possess antiviral, antibacterial, and antioxidant properties, polyphenols are produced as secondary metabolites that are useful to both humans and animals as well as plants (Lomartire et al., 2021). They are defined as compounds with hydroxylated aromatic rings. It has been discovered that phenolic chemicals are effective in food preservation. As plant antioxidants, they exhibit bioactivity and can scavenge reactive forms of nitrogen and oxygen found in meat and other products, such as superoxide, hydroxyl, or peroxyl radicals. This helps to inhibit lipid oxidation processes present in food composites (Gutiérrez-Del-Río et al., 2021). This is particularly significant for fruits and vegetables because they can synthesise these phenolic compounds when exposed to post-harvest conditions like storage, controlled environments, phytohormones (ethylene and methyl jasmonate), radiation (gamma and ultraviolet), thermal shocks, edible coatings, and minimal processing (López-Martínez et al., 2020).

3.1 Phlorotannin

Phlorotannin are dehydro-polymers of phloroglucinol units particularly associated with brown seaweeds (Allwood et al., 2020). They are attached to the subcellular areas of brown algae species and are phenolic metabolites. Seaweed phenolic compounds, like their terrestrial plant counterparts, are mostly composed of hydroxyl groups (-OH). These groups are soluble in water and have a strong bond with proteins, polysaccharides, and biopolymers (Maheswari & Babu, 2022). Phlorotannin have proven to possess potential bioactivities such as antioxidant, antimicrobial, anti-allergic, anti-diabetic, anti-inflammatory, anti-cancerous and neuroprotection (Kumar et al., 2022). They appear to play a defensive role in the seaweeds, protecting against herbivory and UV-B radiation (Allwood et al., 2020). Additionally, the predominant polyphenolic class discovered only in coastal brown seaweeds is phlorotannin. The majority of phenolic compounds identified in green and red seaweeds consist of flavonoids, phenolic acids, phenolic terpenoids, bromophenols, and mycosporine-like amino acids. (Cotas et al., 2020).

3.2 Bromophenols

Bromophenols are phenolic compounds that are prominently found in seaweeds, particularly in red seaweeds (Cotas et al., 2020). A greater percentage of crop production methods are employing seaweed extracts, specifically those that include bromophenols, due to their special bioactive compounds and effects. In certain important agricultural plants, their phytostimulatory properties contribute to enhanced plant growth and yield (Raja & Vidhya, 2023). Their distinctive components and the way they interact with the control of plant development also promote phytohormonal responses (Ali et al., 2021). Seaweed extracts have been found to improve seed germination and plant development throughout the growing season, including post-harvest. A kiwifruit study revealed that an acceptable substitute for chemical treatment for farmers can be to apply a seaweed extract dip at a concentration of 3000 ppm 10 days following the ripening. Seaweed extract-treated fruits were shown to have an extended post-harvest life compared to fruits treated with other chemicals, which resulted into a longer fruit shelf life (Rana et al., 2023).

3.3 Flavonoids

Seaweeds are among a variety of plants that are rich in flavonoids, a family of polyphenolic compounds. Their primary structure has 15 carbon atoms grouped in the C6-C3-C6 configuration. This corresponds to two aromatic rings, A and B, connected by a unit of three carbon atoms that might potentially form a third ring (Vinodkumar & Packirisamy, 2023; Santos et al., 2017Flavonoids have been found to possess a variety of chemical and biological functions in seaweeds, including the ability to scavenge free radicals and act as antioxidants. Vinodkumar and Packirisamy (2023) found that a flavonoid isolated from the brown seaweed *S. myriocystum* from the Rameswaram coastal area of Tamilnadu, India, efficiently mitigated free radicals and proliferation of cells. Flavonoids are expected to be synthesised in seaweeds through the phenylpropanoid pathway (Cotas et al., 2020; Yadavalli et al., 2020). This process converts phenylalanine to 4-coumaroyl-CoA, which then makes its way into the pathway involved in the production of flavonoids. Chalcone synthase, the first enzyme belonging to the flavonoid pathway, develops the chalcone scaffolds that are the source of all flavonoid. (Yu et al., 2024). In order to protect themselves against viruses, peers, biofoulers (epibionts), and predators, seaweeds develop chemical barriers (Amsler, 2012). When the seaweed is attacked, these barriers may be generated naturally or, under certain conditions, their production might be increased. (Bahmani et al., 2023). Flavonoids killed cancer cells by triggering apoptosis and autophagy as part of these defenses (Hosseinzadeh et al., 2023).

3.4 Phenolic terpenoids

Brown and red seaweeds specifically contain a group of metabolites called phenolic terpenoids. They are primarily classified as meroditerpenoids, which are further categorised into plastoquinones, chromanols, and chromenes. These substances are almost entirely found in the family *Sargassaceae* (Cotas et al., 2020).

3.5 Mycosporine-like amino acids

A class of secondary metabolites known as mycosporine-like amino acids (MAAs) were found in many marine organisms, including red seaweeds (Jofré et al., 2020). These are colourless, water-soluble, low-molecular-weight (usually less than 400 Da) compounds. They are made up of rings with nitrogen substituents, either aminocyclohexenone or aminocyclohexenimine. Over 30 MAA structures have been identified, and all involve a core cyclohexenone or cyclohexenimine ring with a wide range of substitutions (Geraldes & Pinto, 2021) Studies have been conducted on the generation of MAAs by *A. armata* seaweed. This economically viable red algal species generated valuable compounds. Numerous study concentrated on the generation and variability of collected biomass of these compounds (Zanolla et al., 2022). Under environmental conditions these MAAs are found to be significantly stable (Chrapusta et al., 2017). They consist of a nitrogen-substituted cyclohexenone or cyclohexenimine chromophore. It is suggested that the ring structure absorbs free radicals and UV rays (Geraldes & Pinto, 2021). Plant organs, fruits, and vegetables have been protected against blisters by emulsions containing MAAs (Salehian et al., 2023). They have the ability to reduce UV-induced oxidative stresses in addition to having a better UV absorption profile (Chen et al., 2023).

4. Important phytohormones in seaweed

4.1 Auxins

Seaweeds are known to contain significant amounts of active plant growth substances such as auxins (Abbas et al., 2020). Auxins are a major class of phytohormones that influence plant growth and development Indolyl-acetic acid is one of the auxins that seaweeds contain the most commonly. The biochemical and physiological processes of plants are influenced by these growth hormones, which increases crop yield (Abbas et al., 2020). Auxins are organic molecules that have an aromatic ring and a carboxylic acid group. Indole-3-acetic acid (IAA) is the most abundant and strong natural auxin, responsible for almost all of auxin activities in intact plants. Further auxins that are synthesized endogenously in plants include Indole-3-butyric acid (IBA), 2-phenylacetic acid (PAA), 4-chloroindole-3-acetic acid (4-CI-IAA), and Indole-3-propionic acid (IPA) (Salazar-Iribe and De-la-Peña, 2020). Throughout plant life cycles, auxins are important for the proper functioning of different growth and behavioral functions as well as the development of the plant's internal structure. They cause plant cells to elongate and enhance cell division, which controls growth. Auxins also affect how stems develop against gravity (geotropism) and towards the light (phototropism) (Zhang et al., 2022). For fruits and vegetables, auxins are critical throughout the post-harvest stage. All aspects of plant physiological processes, such as the development of root buds, contribution to cell division, and tropisms, are controlled by them. Additionally, auxins are involved in fruit development, cell division and differentiation, the growth of roots from cuttings, and leaf abscission (Sosnowski et al., 2023). Auxins can be used to increase vegetative and reproductive development, decrease flower and fruit loss, and help farmers cultivate crops in unfavorable weather conditions.

Table 2. Different extraction techniques for seaweed extract

Seaweed Species	Compound	Extraction method	Parameters	Yield	References
Saccharina japonica (Kelp)	Fucoidan	Hot water extraction with enzymatic assistance	127.01 °C, 80 bar, a solid to liquid ratio of 0.04 g/mL, an agitation speed of 300 rpm, and a reaction time of 11.98 min. Under these conditions	13.56%	Saravana et al. (2017)
Laminaria digitata (Kelp)	Alginate	Alkali extraction (sodium carbonate)	Acidified algae soaked in a 4% Na_2CO_3 solution, 60 min	33.00%	Vauchel et al. (2008)
	Alginate	Reactive extrusion alkali extraction (sodium carbonate)	Twin-screw extruder, 4% Na_2CO_3 solution, barrel temperature 20 °C for 5 min. The sodium alginate solution treated with sulfuric acid, form alginic acid, subsequently dried, milled, and stored at 4 °C.	39.00%	Vauchel et al. (2008)
Undaria pinnatifida (Wakame)	Fucoidan	Microwave-assisted extraction	150 °C for 30 min	12.30%	Sasaki et al. (2022)
Eucheuma spinosum (Red seaweed)	Carrageenan	Ohmic heating	90°C for 180 min. 0.6 M KOH	74.20%	Salengke et al. (2017)
G. gracilis (Red seaweed)	Agarose	Hot water extraction	70°C for 4 h	72.00%	Rodríguez et al. (2009)
Saccharina japonica (Kelp)	Fucoidan	Pressurized liquid extraction	140°C and 50 bar (0.1% NaOH)	8.23%	Saravana et al. (2016)
Laminaria digitata (Kelp)	Alginic acid	Acidified sodium carbonate solution	40°C	51.80 (< 1mm) 44.01 (1-5mm)	Fertah et al. (2017)
Undaria pinnatifida (Wakame)	Total phenolics	Subcritical water extraction	210 °C, at a solid content of 10 g/L, and at 15-20 min.	0.99 mg ± 0.004 mg GAE/g dw	Gan and Baroutian (2022)
	Phlorotannin		210 °C, at a solid content of 10 g/L, and at 15-20 min.	29.9 mg ± 1.8 mg GAE/g dw	
	Fucoidan		20 °C, 5 min, and 20 g/L.	46 mg/g dw	

Table 2. Different extraction techniques for seaweed extract (cont.)

Seaweed Species	Compound	Extraction method	Parameters	Yield	References
G. bursa-pastoris (Red seaweed)	Polyphenols	Distilled water extraction	Ambient temperature, 24 h	381.31 ± 0.33 mg GAE/g	Ouahabi et al. (2023)
	Flavonoids	Distilled water extraction	Ambient temperature, 24 h	201.80 ± 0.21 mg QE/g	Ouahabi et al. (2023)
A. nodosum (Knotted wrack)	Total phenolics	Water methanol extraction	Refluxing at 80°C for 90 min, rotary evaporate 40°C, freeze dried	70.20 PGE%	Zhang et al. (2007)
Ecklonia cava (Brown seaweed)	Phlorotannin	Water ethanol extraction	Solution vacuum evaporated to 20 brix at 50°C and freeze dried	7.50%	Yoon et al. (2017)
	Fucose	Enzyme assisted extraction	Glucoamylase digestion for 12 h, boiled at 100°C for 10 min to inactive enzyme, mix with 99.5% ethanol, centrifuge and freeze dried	82%	Wijesinghe et al. (2011)
Durvillaea potatorum (Bull kelp)	Total Polysaccharides	Acid extraction	0.5 M HCl, 60°C for 3 h	43.57% w/w	Abraham et al. (2019)
	Fucoidan and laminarin	Acid extraction	0.5 M HCl, 60°C for 3 h	7.02% w/w	Abraham et al. (2019)
Hizikia fusiforme (Golden hair seaweed)	Fucoxanthin	Ethanol extraction	40°C for 1 h	0.02 mg/g dw	Kanazawa et al. (2008)
P. palmata (Red seaweed)	Carrageenan	Enzyme assisted extraction	60°C for 14 h, pH 7, centrifuged at 4400 g for 15 min at 4 °C	59.40%	Naseri et al. (2020)

GAE: gallic acid equivalent; QE: quercetin equivalent; PGE%: phloroglucinol equivalent; dw: dry weight, w/w: weight/weight

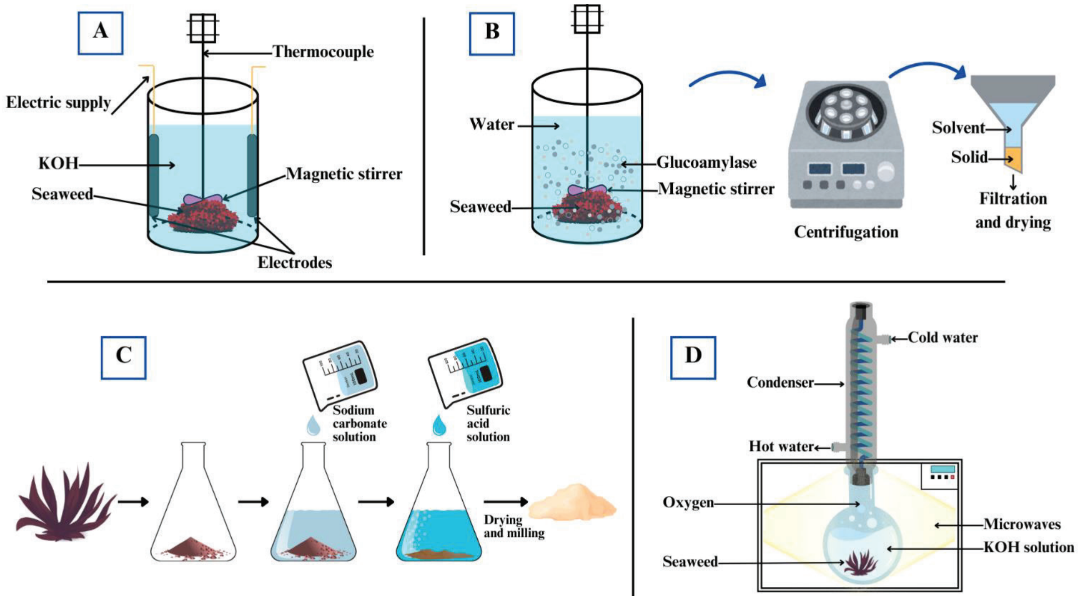

Figure 1. Different techniques for seaweed extract

4.2 Cytokinin

Plant growth compounds known as cytokinin enhance the process of cell division, or cytokinesis, in the roots and shoots of plants. They are present in a variety of plant materials, such as seaweed (Yokoya et al., 2023). Cytokinin play an important role in growth and development of seaweeds. A commercial preparation of Tasmanian giant bull kelp called Seasol, which is sold as a liquid organic fertilizer, was shown to contain cytokinin glucosides by Tay et al. (1987). The two most common cytokinin-O-glucosides found were dihydrozeatin riboside-O-glucoside and zeatin-O-glucoside, together with its dihydro derivative. Yokoya et al. (2023) examined cytokinin-like (CK) activity in eight species, including carrageenophytes (*Chondracanthus, Hypnea*) and agarophytes (*Gracilaria* spp.*, Gelidium*). The majority of the activity of the green strain of *Hypnea psedomusciformis* co-chromatographed with zeatin, showing that it is more active than the brown strain. These investigations demonstrate the potential of seaweeds as a source of cytokinin, which has use in agriculture as bio stimulants.

4.3 Gibberellins

A class of hormones found in plants called gibberellins is essential to many stages of growth and metabolism. They are present in many plants, including seaweeds. The red seaweed *K. alvarezii* consists of gibberellic acid (GA3) and other hormones, according to a study conducted by Mondal et al. (2014). This seaweed's sap has been sprayed on leaves and has been proved to significantly increase crop yields in several cases. To get sap compositions free of GA3, selective solvent extraction was used in this study. In comparison to the pristine sap, it was found that the GA3-free sap increased photosynthetic activity, resulting in a 26% increase in maize stover production. This is believed to take place because GA3 and other hormones are prevented from developing negative interactions. Gibberellins were also discovered in another study conducted by Stirk et al. (2013) on the large brown seaweed *Ecklonia maxima.* This seaweed is utilised in the manufacturing of consumer goods, fertilisers for agriculture, and nutrition for humans. Despite the great chemodiversity of gibberellins found in plants, only GA1, GA3, GA4, and GA7 were shown to have biological activity that regulates plant growth (He et al.,2020). Gibberellins have been found to have major functions in prolonging the ripening and senescence of horticultural crops. They improve quality, and increase the resistance to disease and stress. They can considerably increase flesh hardness, decrease respiration intensity, prevent the release of endogenous ethylene, and successfully prevent fruit from softening and ripening. They can also effectively improve the quality of fruit storage (Zhang et al., 2023). Gibberellins also play a role in postharvest biotic and abiotic stress resistance.

4.4 Abscisic acid

ABA is a plant hormone that plays a crucial role in plant growth and development (Dörffling, 2015). ABA has been found to activate antioxidant tolerance responses to desiccation stress in seaweed. According to a Guajardo et al. (2015) study, ABA influences the oxidative stress state under desiccation, an environment brought on by daily tidal fluctuations, in the intertidal seaweed species *Pyropia orbicularis, Mazzaella laminarioides,* and *Lessonia spicata*. According to the study, *Pyropia orbicularis* overproduced free ABA when there was a shortage of water. The regulation of antioxidant enzyme activation during desiccation by ABA was discovered through the application of ABA inhibitors. High cell survival and minimal lipid peroxidation were seen in those exposed to exogenous ABA, which was accompanied by an increase in enzyme activity. ABA plays a major role in the ripening process. In most fruits, ABA levels increase during the ripening process. Applying ABA externally can accelerate softening, facilitate colour development, and improve fruit flavor through sophisticated signal regulation (Wu et al., 2023). In order to control different fruit properties and improve their suitability for consumption or storage, it is important to understand the processes by which ABA affects fruit ripening. Plants are reported to be more resistant to a range of abiotic stressors when seaweed extracts are applied, which are rich in phytohormones like ABA (Panda et al., 2022). Although further research is required in this area, this indicates that seaweed extracts can be utilised to increase the shelf life of fruits and vegetables.

5. Seaweed extract in post-harvest management

Azeez et al. (2020) investigated the high gelling capability of two different seaweed species: *S. tenerrimum* (brown algae) and *K. alvarezii* (red algae). The results revealed the presence of phytonutrients such as tannins, steroids, flavonoids, and saponins in the two chosen seaweeds. Comparing *K. alvarezii* to *S. tenerrimum*, the latter showed less antimicrobial and antifungal activity against common pathogens. The shelf life of the tomatoes was evaluated after coating them with various ratios of the seaweed extract (gel). A 3% *K. alvarezii* coating seemed to be the most effective with increased juice yield when it came to protecting the texture and prolonging the shelf life of tomatoes. Another study by Omar (2014) treated the Navel orange (*Citrus sinensis Osbeck*) post-harvest using an extract from sargassum, a brown seaweed. It has been found that introducing 4% seaweed extract decreased weight loss to 5.06% and fruit rot to 9.09% at room temperature, and to 4.94% and 4.47% at cold temperatures. The authors suggested seaweed extracts as a viable and effective natural substitute for chemical fungicides in post-harvest dipping treatments. Pre-harvest foliar application of amino acids and extract from *A. nodosum* seaweed was examined by Khan et al., (2018) in relation to the growth, yield, and storage life of several hydroponically grown bell pepper (*Capsicum annuum* L.) cultivars, including Sven Rz F-1 and Red Knight. When 3 mL of amino acids and 4 mL of seaweed were added, there was an increase in the quantity and size of leaves. This may be explained by the hormone-acting phosphatases, ferric chelate reductase activity, and nitrate reductase found in seaweed extract. Ghafouri et al. (2023) investigated the postharvest traits improvement of kiwi fruit (*Actinidia deliciosa* L. cv. Hayward) by application of seaweed (*A. nodosum*). Seaweed extract of 3 g/l improved the firmness by 40.40%, fruit weight loss percentage by 41.87%, titratable acid by 25.37%, vitamin C by 33.26%, antioxidant capacity by 26.70%, total phenol by 81.17%, total flavonoids by 103.67% and PAL enzyme activity by 153.75% compared to the control in 90 days of storage. The addition of seaweed and amino acids helped to offset the fruit's gradually loss of firmness. For "Sven Rz F-1" and "Red Knight," the highest firmness was 5.56 and 6.57, respectively, after treatments with 3 mL L1 amino acids and 4 mL seaweed. Ghafouri et al. (2023) studied the effects of spraying seaweed (Ascophyllum nodosum) on improving the postharvest qualities of kiwi fruit (*Actinidia deliciosa* L. cv. Hayward). After 90 days of storage, a 3 g/l seaweed extract increased the total phenol by 81.17%, total flavonoids by 103.67%, PAL enzyme activity by 153.75%, titratable acid by 25.37%, vitamin C by 33.26%, antioxidant capacity by 26.70%, and fruit weight loss percentage by 41.87% when compared to the control. The impact of *A. nodosum* seaweed extract on post-harvest 'Tommy Atkins' mangoes was investigated by De Melo et al. (2018). Mangoes were kept for 12 days at 25±2 °C in temperature and 75±5% relative humidity after being treated with different doses of seaweed extract (0,1%, 0.3%, 0.5%, and 1.0%). When compared to the control (0% seaweed extract), fruit mass loss was effectively reduced by seaweed extract, with a reduction of up to 40.2% observed at the 0.1% dose. The colour angle hue of the seaweed extract concentrations did not differ from one another; nevertheless, on the 12th day in specific, all of them exhibited hue values that were greater than those of the control. The findings indicate that a different approach to mango preservation in the post-harvest phase would be the use of seaweed extract. The quality and shelf life of the mangoes may be improved by implementing this.

A number of studies have focused on screening seaweed extracts to find novel antifungal chemicals that might replace or supplement commercial fungicides in the management of postharvest diseases. It has been shown that extracts from the edible seaweed *Osmundea pinnatifida* exhibit antifungal properties against *Alternaria alternata* and *Aspergillus fumigatus,* preventing their proliferation and conidiation (Silva et al.,2018). *In vitro* studies showed that the preharvest treatment's polysaccharides from the three seaweeds, *Anabaena* sp*., Ecklonia* sp*.,* and *Jania* sp*.,* decreased the infected area of strawberry fruit as well as the pathogen's sporulation (Righini et al., 2019). On the same fruit, *A. nodosum* seaweed extract was able to reduce the soft rot incidence caused by the infection of *Rhizopus stolonifer* in the postharvest stage (Mattner et al., 2023).

6. Conclusion

In the field of post-harvest management, seaweed extracts have been a game-changer by providing a viable and efficient method of fruit and vegetable preservation. The present review provided insight into the various advantages of seaweed extracts, highlighting their capacity to simulate and improve plant development processes by means of their concentration of crucial phytohormones such as auxins, cytokinin, gibberellins, and ABA. The beneficial effects of these hormones convert into a variety of practical advantages. Seaweed extracts prevent weight loss, keep fruits and vegetables firm, and even boost their nutritional value, all of which contribute to a longer shelf life. As a result, there is a noticeable decrease in food waste and consumers can enjoy fresh, premium products for a prolonged period.

Seaweed extracts are an incredibly promising substitute for synthetic fungicides, which are frequently linked to negative health and environmental effects. Their antifungal capabilities support sustainable farming operations by providing a natural and profitable method for preventing post-harvest diseases. However, further study is required before this technology can be effectively utilised. Future research must focus on determining the best seaweed species and concentrations for specific crops as well as refining extraction techniques to ensure optimal efficiency. Further research is necessary to fully understand the underlying processes via which seaweed extracts affect plant physiology in the post-harvest stage. Their ability to increase disease resistance, enhance shelf life, improve quality, and provide an alternative for commercial fungicides provides the potential to a more effective and sustainable food system.

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