

REVIEW ARTICLE

Seaweed-Derived Bioplastics: A Sustainable Alternative to Petroleum Based Plastics: Review

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HOW TO CITE THIS ARTICLE:

Kinjal Upadhyay, Palak Yagnik. Seaweed-Derived Bioplastics: A Sustainable Alternative To Petroleum-Based Plastics: Review. J Microbiol Relat Res. 2025; 11(2): 91–103.

ABSTRACT

The increasing environmental burden of conventional plastic pollution particularly from packaging waste has intensified the global pursuit of sustainable, biodegradable alternatives. Seaweeds, or marine macroalgae, have emerged as promising renewable biomass for bioplastic production due to their rapid growth, abundant polysaccharide content, and non-reliance on freshwater or arable land. This review critically examines the recent advancements (2010–2025) in the development of seaweed-derived bioplastics, focusing on the extraction of biopolymers such as alginate, agar, and carrageenan from brown and red algae.²⁰

Key fabrication methods, including solution casting and extrusion, are explored alongside mechanical and biodegradation properties of the resulting materials. For instance, alginate-based films have demonstrated tensile strength values up to 38 MPa, while carrageenan films are noted for their transparency and potential for blending. Biodegradability tests have shown that certain seaweed bioplastics degrade within 30–60 days under natural conditions, offering significant environmental advantages.²¹

The review also highlights challenges such as water sensitivity, mechanical brittleness, and higher production costs, while identifying potential solutions in polymer blending, nanocomposites, and green extraction techniques. By synthesizing findings across multidisciplinary studies, this review underscores seaweed's potential as a sustainable raw material for biodegradable plastics and its role in addressing the global plastic crisis.²⁰

KEYWORDS

• Seaweed • Bioplastic • Pollution • Seaweed-extraction

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➤ Received: 05-08-2025 ➤ Accepted: 27-09-2025



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INTRODUCTION

Plants are the primary producers for the precious life to run on earth. They form the basic direct food for the herbivores and indirectly to the carnivores and hence form part of food web/chain. They are classified into Phanerogams and Cryptogams. The cryptogams are again divided into Thallophyta, Bryophyta and Pteridophyta. Algae and Fungi are grouped under Thallophyta. Algae are mostly aquatic and grow in various types of waters. Some algae occur in soil and air. They are the primitive group of plants evolved first in the universe and are microscopic as well as macroscopic commonly known as microalgae and macroalgae respectively. In general, macrophytic algae present in marine environment (Seas/Oceans) are called seaweeds.³

Seaweeds, otherwise known as marine algae are primitive non-flowering photosynthetic macrophytes occurring in tidal regions of seas and oceans that occupy 71% of the globe

and they are natural renewable resources. Green, brown and red seaweeds are generally distributed in the intertidal, tidal and subtidal regions respectively.³

Classification of seaweeds Based on pigmentation:

Seaweeds can be classified into three broad groups: brown, red and green. Botanists refer to these broad groups as Phaeophyceae, Rhodophyceae and Chlorophyceae, respectively. Brown seaweeds are usually large and range from the giant kelp that is often 20 m long, to thick, leather-like seaweeds from 2-4 m long, to smaller species 30-60 cm long. Red seaweeds are usually smaller, generally ranging from a few centimetres to about a metre in length; however, red seaweeds are not always red: they are sometimes purple, even brownish red, but they are still classified by botanists as Rhodophyceae because of other characteristics. Green seaweeds are also small, with a similar size range to the red seaweeds.⁴

Brown Seaweeds (Phaeophyta)						
						
<i>Ascophyllum nodosum</i>	<i>Cystoseira indica</i>	<i>Durvillaea antarctica</i>	<i>Hizikia fusiforme</i>	<i>Labophora variegata</i>	<i>Sargassum filipendula</i>	<i>Sargassum kjellmanianum</i>
Green Seaweeds (Chlorophyta)						
						
<i>Caulerpa prolifera</i>	<i>Caulerpa cuprescoides</i>	<i>Caulerpa lentillifera</i>	<i>Cladophora rupestris</i>	<i>Codium fragile</i>	<i>Halimeda opuntia</i>	<i>Ulva lactuca</i>
Red Seaweeds (Rhodophyta)						
						
<i>Boergeseniella thuyoides</i>	<i>Bryothamnion triquetrum</i>	<i>Corallina officinalis</i>	<i>Chondrus crispus</i>	<i>Gelidium latifolium</i>	<i>Kappaphycus alvarezii</i>	<i>Sphaerococcus coronopifolius</i>

Source: https://www.researchgate.net/figure/mages-of-brown-green-and-red-seaweed-species_fig1_381255716

Sources of seaweed:

Brown seaweeds: Brown seaweeds are more useful and grow in cold waters in both the Northern and Southern Hemispheres. They thrive best in waters up to about 20°C. Brown seaweeds are found in warmer waters, but these are less suitable for alginate production and rarely used as food.⁷

Red seaweeds: Red seaweeds are found in cold waters such as Nova Scotia (Canada) and southern Chile; in more temperate waters, such as the coasts of Morocco and Portugal; and in tropical waters, such as Indonesia and the Philippines. Most of the raw material used for the extraction of agar comes from two genera, *Gelidium* and *Gracilaria*. The original source of carrageenan was the red seaweed *Chondrus crispus* (common name: Irish Moss).⁷

Over the past century, plastic has become a ubiquitous material due to its versatility,

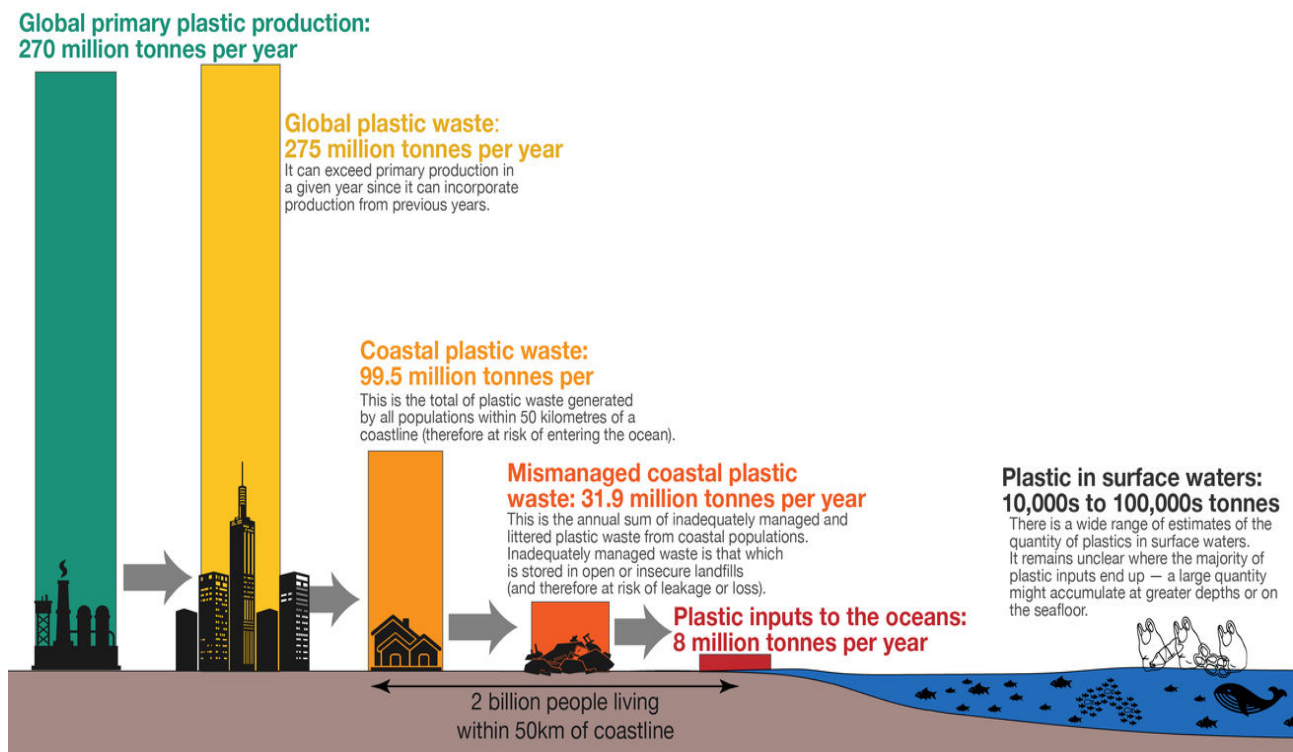
durability, and low production cost. Plastic pollution, more specifically from food packaging and containers which account for the largest share of 36% of current plastic production, is one of the greatest threats to the natural environment and human health. Plastics also have very slow decomposition rates and as such, pose several environmental concerns as plastic particles have spread across the world's oceans contributing largely to contamination in the food chain. Thus, the development of alternative renewable plastics are needed to complement a circular economy and reduce resource depletion.¹⁷

Given the urgent need to curb plastic pollution, the development of sustainable, biodegradable alternatives is crucial. Seaweed-derived bioplastics offer one such promising solution, aligning environmental sustainability with material utility.¹⁶

The pathway by which plastic enters the world's oceans

Our World in Data

Estimates of global plastics entering the oceans from land-based sources in 2010 based on the pathway from primary production through to marine plastic inputs.



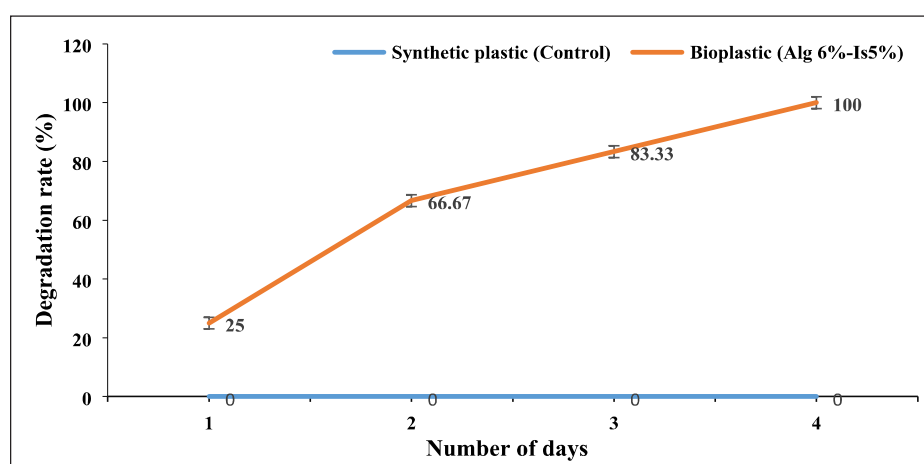
Source: based on Jambeck et al. (2015) and Eriksen et al. (2014). Icon graphics from Noun Project.

Data is based on global estimates from Jambeck et al. (2015) based on plastic waste generation rates, coastal population sizes, and waste management practices by country.

This is a visualization from [OurWorldinData.org](https://ourworldindata.org), where you will find data and research on how the world is changing.

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Source: <https://ourworldindata.org/plastic-pollution#impacts-on-wildlife>, https://en.m.wikipedia.org/wiki/Marine_plastic_pollution



Source: https://www.researchgate.net/figure/Bioplastics-degradation-rate_fig6_362493063

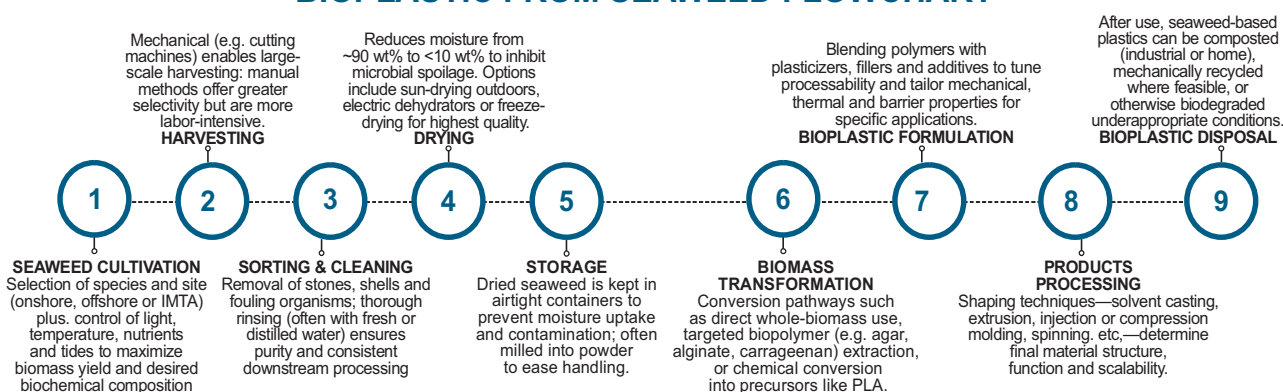
Components of Seaweed:

Carbohydrates are the major components of most seaweeds, mainly found in the form of polysaccharides, typically ranging from 4% to 76% of their dry weight. The polysaccharides from macroalgae of commercial importance are alginate (30,000 tons/year, 12 USD/kg), carrageenan (60,000 tons/year, 10.4 USD/kg), and agar (10,600 tons/year, 18 USD/kg). Alginate is a linear polysaccharide mainly extracted from brown algae, which can be found in its acid form, as alginic acid or as a salt-forming part of the cell wall. Its structure is composed of two hexuronic monomers, α -1-glucuronic acid (G) and β -D-mannuronic acid (M), linked by (1-4)-glycoside linkages.¹⁹ Carrageenans are linear polysaccharides which can be found in the cell wall of mainly red algae, formed by alternating chains of sulphated and non-sulphated galactose chains linked by glycosidic bonds. Agar is also extracted mainly from red algae and consists of a mixture of polysaccharides composed of agarose and agaropectin. The most widespread use of alginate,

carrageenan, and agar extracted from seaweed is as a gelling and thickening agent in the food industry.¹⁹

The protein fraction found in seaweeds is also very variable depending on the seaweed type, the season, and place of collection. Brown seaweeds are the ones with the lowest protein content, with a maximum of ~20% (dry basis). On the other hand, green and especially red seaweeds have, in general, a higher protein content, comparable with vegetables such as soybeans or other legumes (~40%, dry basis). Thus, the nori variety is a red seaweed with up to 32.2% protein content, while green seaweeds such as some from the *Ulva* family contain up to 38.16%. These proteins have an amino acid composition like that of legumes, glutamic acid and aspartic acid being the most abundant amino acids. On the other hand, free amino acid fractions are composed mainly of alanine, aminobutyric acid, citrulline, hydroxyproline, ornithine, and taurine, the amount depending on the species of seaweed.¹³

BIOPLASTIC FROM SEAWEED FLOWCHART



Flowchart of making Bioplastic from Seaweed

The lipid content is generally low in seaweeds compared to animal sources, with a ~1–5% (dry basis) of lipids, its fatty acid profile depending on the species and environmental conditions. Regarding this, a higher percentage of fatty acids has been observed in winter or

spring than in summer and in cold-water species compared to tropical ones. The lipids of marine algae are mainly composed of polyunsaturated fatty acids, the content of which increases in species from cold climates.¹⁹

Seaweed cultivation:

	Onshore Cultivation	Offshore Cultivation	IMTA
<i>Technologies</i>	Photobioreactors, controlled tank systems.	Rope & line systems, floating farms, use of buoys for stability.	Integrated systems combining seaweed with fish or shellfish farming.
<i>Scalability Potential</i>	Medium; requires infrastructure for controlled environments.	High; scalable for large ocean-based operations.	High; integrates with other aquaculture enhancing scalability.
<i>Costs</i>	High initial & operational costs due to infrastructure.	Medium; lower initial costs, ongoing maintenance required.	Medium; shared costs with other aquaculture activities.
<i>Impact on quality and yield</i>	High; controlled environment ensures quality & optimised biopolymer content.	Variable; dependent on environmental conditions that may affect biochemical composition.	High; nutrient rich environment enhances quality.
<i>Environmental impact</i>	Medium; energy intensive, but low water contamination.	Low; integrates with natural ecosystem.	Positive; reduces environmental effect of other aquaculture.
<i>Carbon sequestration</i>	Moderate; depends on the species and growth rate.	High; Significant potential, especial for kelp species.	High; chances of carbon sequestration.
<i>Biodiversity impact</i>	Low; limited to controlled environment, minimal impact on local diversity.	Moderate; can enhance local marine biodiversity but may disrupt ecosystems if not managed properly.	High; promotes diversity by integrating multiple species and trophic level.
<i>Regulatory challenges</i>	High; stringent controls required for water use, waste management & species protection.	Moderate; subject to maritime laws and environment regulations.	High; must comply with regulations for aquaculture and environmental protection.
<i>Bioplastic production potential</i>	Best for specialized, high quality bioplastics.	Suitable for mass production of feedstocks for bioplastics.	Diverse outputs can support various bioplastic

Harvesting:

	Mechanical Harvesting	Manual Harvesting
<i>Techniques/Technologies</i>	Mechanical cutters, automated harvesters with quality sensors.	Hand Picking.
<i>Scalability</i>	High; ideal for large scale bioplastics feedstock.	Low; best for niche or high value bioplastics.
<i>Costs</i>	High initial investment, low labour costs.	Low initial costs, high ongoing labour.
<i>Impact on quality and yield</i>	Medium; potential damage could affect biopolymer yield and extraction quality.	High; careful selection preserves quality.
<i>Energy consumption</i>	High; necessary for large scale operations.	Low; minimal energy usage, labour intensive.
<i>Extraction efficiency</i>	Medium; Risk of contamination or damage during harvesting could lower efficiency.	High: selective harvesting ensures high quality outputs.
<i>Suitability for bioplastic production</i>	Best for mass production where quantity is prioritized.	Suitable for high quality, high value bioplastic.

Drying:

Drying is one of the most critical steps in feedstock preparation as it preserves the seaweed biomass by reducing its moisture content from around 90% to below 10%, where 10 kg of fresh seaweed typically produces 1 kg of dried biomass. The selected drying method can significantly affect the quality of the seaweed and the properties of the bioplastic produced, requiring a balance between energy consumption and the preservation of biochemical properties. This balance is crucial for ensuring the feedstock's suitability for further processing and its contribution to the overall sustainability of the bioplastic lifecycle. Several drying techniques are employed, each with its advantages and limitations.²⁰

Sun-drying and shade-drying. These traditional methods are cost-effective and involve spreading the seaweed under direct sunlight or in shaded areas until fully dried. While sun-drying is energy-efficient, it may lead to uneven drying and contamination from environmental factors like dust or soil. Shade drying, on the other hand, can take longer, typically 3-4 days, offering more protection but less practical for large-scale operations.²⁰

Commercial dehydrators and ovens. These methods provide controlled environments for drying, ensuring uniform moisture removal. For example, drying at 60°C for 12-24 hr can be effective. However, the energy intensity of these methods requires careful consideration, particularly when scaling up production. Combining sun-drying and oven-drying is also common to semi-dry seaweed after harvesting and before transportation.²⁰

Freeze-drying. Although more energy-intensive, freeze-drying preserves the seaweed's biochemical and structural integrity by sublimating moisture without passing through the liquid phase. This method is particularly useful for high-value applications where maintaining the highest quality is paramount.²⁰

Extraction:

Most conventional extraction processes (e.g., soxhlet, solid-liquid extraction, or liquid-liquid extraction) are characterized by long extraction times and comprise hazardous acidic and alkali treatments. These conventional

extraction methods are also associated with both low selectivity and extraction yields of bioactive compounds. To tackle these issues, the scientific community has been looking for eco-friendly and efficient approaches following the Green Chemistry principles, aimed at supporting scientists and engineers on the design of new materials. Those techniques are mostly based on compressed fluids, including Supercritical Fluid Extraction, Pressurized Hot Water Extraction, and Pressurized Liquid Extraction, also known as Accelerated Solvent Extraction.^{36,37}

Alginate (ALG), fucoidan (FU) and laminarin (LAM) are extracted from marine brown algae (Phaeophyceae). Additionally, FU can also be extracted from some marine invertebrates (sea urchins and sea cucumbers). Although LAM is still relatively unexplored, it has recently attracted the attention of the scientific community in the biomedical field due to its low viscosity, cytocompatibility and biocompatibility.³⁷

Polysaccharides extracted from brown algae display biological properties, including antioxidant, anticoagulant, antiviral, anti-inflammatory, immunomodulation, and antitumor activities, highlighting their importance in the biomedical field. These polysaccharides have been usually extracted from brown algae through several time-consuming extraction approaches, namely hot water, dilute alkali or acid, and various purification and fractionation processes.^{37,38}

Therefore, alternative methods encompassing less extraction times and the use of non-harsh solvents have been investigated, including microwave-assisted extraction (MAE) combined with hydrothermal treatment. One work has investigated a wide range of operational conditions (reaction time, pressure and alga/water ratio), aiming at establishing the best ones that could maximize the FU extraction yield. The optimal extraction conditions (pressure 120 psi, 1 min extraction and 1/25 (g ml⁻¹) algae/water ratio) have afforded a FU extraction yield of 18.2%. In another work, the microwave-hydrothermal extraction was combined with supercritical carbon dioxide to remove the lipid fraction from the seaweed, prior to FU recovery.³¹

Production methods	Principle	Advantage (+) Disadvantage (-)
<i>Enzyme-assisted extraction</i>	Enzymes such as protease and carbohydrase break down the cell wall and release algal polymers.	+High efficiency, environmentally friendly, wide chemical selectivity -Slow process, expensive enzyme
<i>Microwave-assisted extraction</i>	Microwave irradiation raises the temperature and penetrates the cell wall to release the polymers into the solvent.	+Fast process, high yield, low solvent consumption, scalable -High equipment cost, explosion risk, solvent must be polar and non-volatile
<i>Extraction by photo-bleaching</i>	Sunlight is used to remove pigment through photolysis, where the sulphate content of polymers is reduced.	+Environmentally friendly, chemical-free, improves the quality of extracts, improves efficiency -Affected by weather conditions, causing chemical changes in samples
<i>Reactive extrusion</i>	Mixing, shearing, heating are used to initiate chemical reactions, homogenize and melt materials to form a polymer.	+Fast and continuous processing, low solvent consumption, expandable -High equipment cost can cause thermal degradation of seaweed
<i>Pressure solvent extraction</i>	The high pressure and solvent temperature below the boiling point are used to extract the polymers in a short time.	+Green solvent and low consumption, efficient, fast process, simple steps -High equipment cost can cause thermal degradation of seaweed
<i>Supercritical fluid extraction</i>	The solvent (usually CO ₂ or H ₂ O) is at the critical temperature and pressure for polymer extraction.	+ Eco-friendly, fast process, high purity extracts, cheap and recyclable solvent -High equipment cost, operation cost and energy consumption, big volume problem
<i>Ultrasound-assisted extraction</i>	Sound waves of more than 20 kHz penetrate the solvent within the cell wall and generate cavitation bubbles to remove polymers.	+Fast process, low solvent and energy consumption, high efficiency, waste-free, simple steps, easy scale-up -High equipment cost, narrow selectivity solvent

BROWN SEAWEED POLYSACCHARIDES

Brown seaweed, Phaeophyceae, are widespread macro algae growing abundantly at northern latitudes in marine cold waters, although some species are indigenous to fresh and brackish waters. Brown algae contain a carotenoid pigment, fucoxanthin, providing the plant's characteristic brown color by suppressing other pigments. The sizes of brown algae plant bodies range from a few millimeters up to some 70m, indicating a variety in structure and composition between species within the same algal class.²⁵

Brown macroalgae consist of a complex and dynamic cell wall rich in polysaccharides, such as alginate (also alginic acid and algin), fucoidan (also fucoidin and fucan), laminarin (also laminaran), and cellulose, but also containing polyphenols, proteins, glycoproteins, phlorotannins (sulfated phenolic compounds), halogens such as iodine, and minerals, such as sodium, potassium, calcium and magnesium.²⁶ The relative content of different compounds varies between species and is highly dependent on seasonal, environmental and

regional factors. Additionally, while alginate seems to constitute a significant part of all brown algae, laminarin and fucoidan appear to occur more frequently in some species, such as *Laminaria* spp. and *Fucus* spp., than in others. The presence of free sugars, such as glucose, fructose and sucrose in brown algae is insignificant, since monomeric sugars are immediately converted into d-mannitol and polysaccharides. Glucose content, for instance, is seasonally dependent, bound mainly in the beta-glucan, laminarin that acts as storage polysaccharide in the cells.²⁵

The cell wall of brown algae consists of fucose containing sulfated polysaccharides (FCSPs) as a major crosslinking glycan in the cell walls, interlocking the cellulose microfibrils situated in layers parallel to the cell surface that constitute the framework of the cell. They also suggest that short fragments of hemicellulose are intermediate links between cellulose and the cross-linking FCSPs, although the composition of these proposed hemicellulose fragments is not defined. These structures are embedded in a matrix of alginates. The cell

wall matrix is postulated to consist of mainly alginates, proteins, polyphenols (linked to both these compound groups), and iodine. Cellulose and/or mixed linkage glucans, comprising only a minor fraction (<10% DW), may also have a structural role in the cell wall as microfibrils associated with fucoidan or alginate.²⁵

Brown algae appears to have emerged later in time than red algae, green algae and terrestrial plants. No unicellular brown algae species have been found, and the development of the multicellularity and plant-like structures of brown algae occurred isolated from other algae and plants. However, brown algae have cell wall polysaccharides in common with plants (cellulose), animals (sulfated fucans) and bacteria (alginate). Although brown algae comprise a wide variety of compounds, most focus and research has been directed towards the utilization of algal polysaccharides, especially fucoidan, alginate and laminarin.²⁵

Red Seaweed Polysaccharides:

Red seaweed, Rhodophyta, is a group of mainly multicellular photosynthetic eukaryotic organisms, reported to comprise more than 7000 species. They grow mostly in marine habitats, but up to 5% of species can grow in freshwater environments, with greater numbers in warmer areas. The red color is expressed due to the predominance of the pigments phycocyanin and phycoerythrin over other pigments such as chlorophyll A and carotene. Red algae store sugars as floridean starch, a highly branched amylopectin without amylose, which is accumulated outside the plastid in the cytosol of the cells. The cell wall of the seaweed is mainly composed of cellulose, carrageenan and agar, which all have several industrial applications.^{25,26}

Green Seaweed Polysaccharides:

Green seaweeds are members of the Chlorophyta, which include the majority of the described species of green algae. Members of the Chlorophyta are inhabitants of both marine and freshwater systems. Marine macroalgae (the focus in this review) from the classes of Chlorophyta in principle involve the class Ulvophyceae and mainly include candidates from the orders Ulvales-Ulotrichales, Cladophorales, and Bryopsidales, including species that display large morphological and cellular diversity. Well known genera classified

under Ulvophyceae include various edible species of *Ulva*, *Gayralia* and *Monostroma* (classified under the order Ulvales-Ulotrichales), *Cladophora* (Cladophorales), *Caulerpa* and *Codium* (Bryopsidales), all of which have been used in human diets in different parts of the world. Despite this traditional use, green seaweeds are not as well researched as red and brown, and although having potential, they lack major industrial applications, such as those seen for red and brown algae.⁴⁰

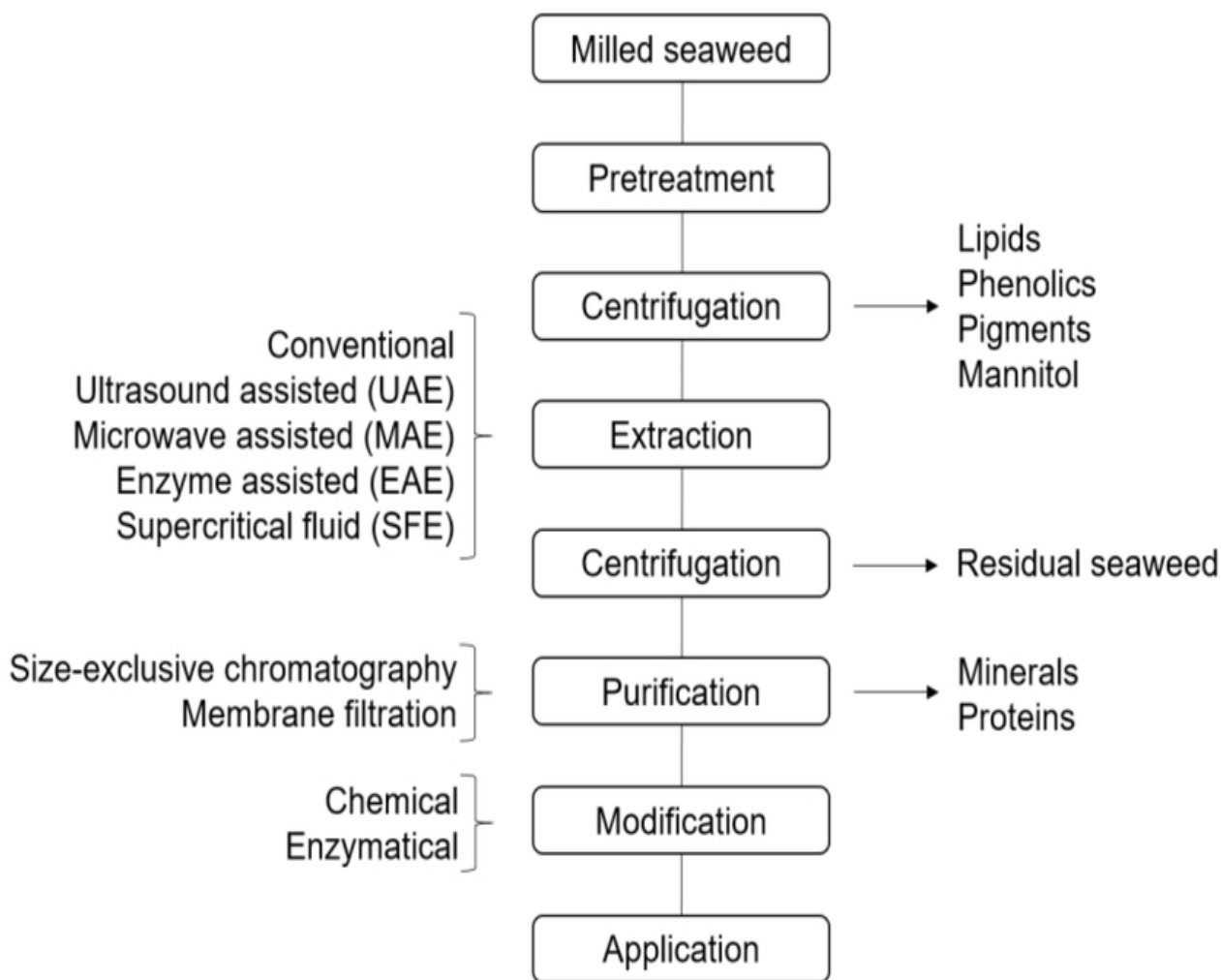
Green seaweeds contain interesting polysaccharides that are sulfated and/or carboxylated. The backbones of the main polysaccharides differ in candidate species from different genera, but roughly, they can be divided into two major groups that are classified as uronic acid rich or uronic acid limited. The uronic acid rich (sulfated) polysaccharides are represented by the ulvans that can be found in various species of *Ulva*, *Gayralia* and *Monostroma*. The composition of ulvan is reported to be dependent on species, season, growth conditions, as well as on the method of isolation.⁴⁰

Extraction of Brown Seaweed Polysaccharides:

For brown algae, a calcium compound (usually CaCl_2) can be introduced to the polysaccharide fraction during extraction to precipitate alginate, and thereby separate laminarin from the alginate fraction, while fucoidan is present in various amounts in both fractions. Sulfated polysaccharides in the supernatant are often precipitated with ethanol, and further purification steps often repeated extractions in acid followed by precipitation, size-exclusive chromatography, or filtration can be applied to achieve pure fucoidan. It has been suggested to always include a benchmark procedure when employing new extraction methods for fucoidan, in order to get better comparisons of fucoidan structures. The extraction of laminarin is predominantly performed at increased temperatures, since the water solubility of different forms of laminarin vary. Branched forms tend to be more water soluble than non-branched. Alginates, being industrially produced from brown macroalgae, are commonly extracted by several ion-exchange procedures using either the 'acid precipitation method' or the 'calcium precipitation method'.⁴¹ Simplified, water-insoluble divalent alginate gel or alginic

acid gel are swelled in acidic water prior to extraction. Sodium-containing compounds are then introduced to convert the divalent alginate into water-soluble sodium alginate during extraction. Aqueous alginate is highly viscous and must be diluted prior to clarification and filtration. The typical yield

of alginate extraction is usually higher than that of fucoidan and laminarin. However, different isolation methods seem to affect the mannuronic/guluronic acid ratio (M/G ratio) of the extracts differently, which impacts the gelling properties of alginate.⁴²



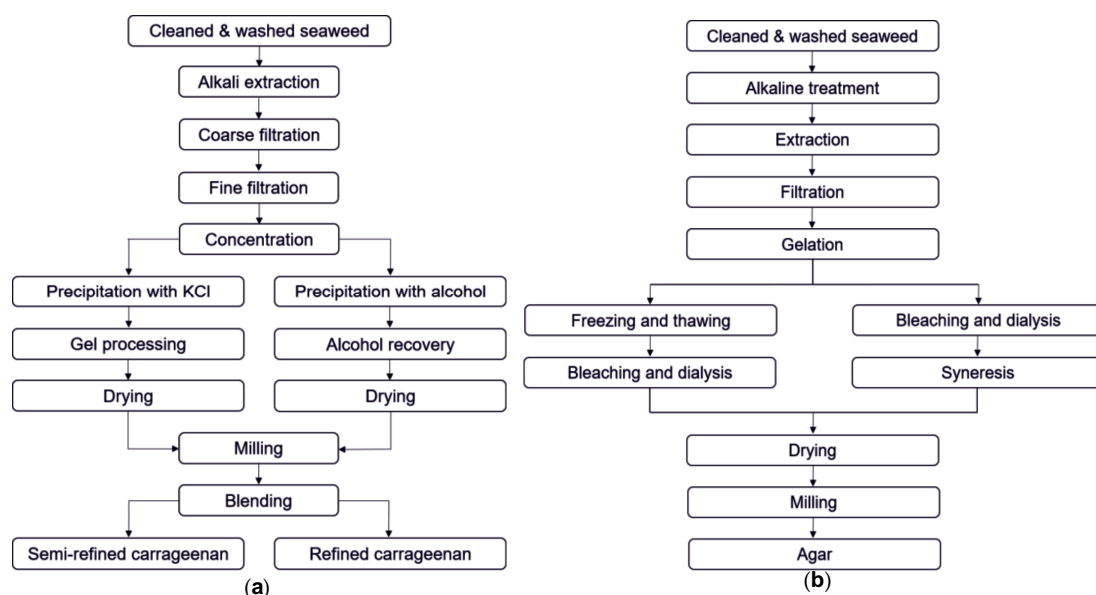
Source: www.researchgate.net/figure/Basic-flow-chart-of-extraction-of-polysaccharides-from-brown-macroalgae_fig1_339503598

Extraction of Red Seaweed Polysaccharides:

Carrageenan is extracted from several species of red seaweed including *Hypnea*, *Gigartina*, *Chondrus*, *Eucheuma*, *Kappaphycus*, and *Mastocarpus*. In conventional extraction, an alkali solution is used to extract carrageenan, because in alkaline conditions some of the sulfate ester groups are removed with the formation of 3,6-anhydro-d-galactose units, thus improving gel strength. Extraction parameters such as operation time, temperature, concentration of alkali, and the ratio between the weight of the seaweed and

the volume of the alkali solution depend on the seaweed species and the desired quality of extracted carrageenan.⁴¹

There are two conventional extraction procedures to extract refined carrageenan (RC) and semi-refined carrageenan (SRC). In RC production, carrageenan is solubilized in hot water containing alkali, such as sodium hydroxide, and the remaining insoluble compounds are separated via filtration. The solution containing carrageenan is concentrated and carrageenan is subsequently precipitated by alcohol, dried and milled.⁴¹



Source: www.researchgate.net/figure/Conventional-extraction-method-of-refined-carrageenan-RC-and-semi-refined-carrageenan_fig2_339503598

(a) Extraction method of refined & semi-refined Carrageenan (b) Extraction method of Agar

Improving Carrageenan films with Nanoparticles:

Carrageenan provides an excellent gelling ability and a high solubility and swelling in water, making it biodegradable, and it has been extensively used in food and packaging. However, although biopolymers are environmentally friendly, they have a primary limitation of a shorter lifetime, mainly because of their hydrophilic, poor barrier, and thermomechanical properties. This limitation made carrageenan-based biopolymers less in demand as food packaging since food packaging must have good barrier properties to protect its content against external forces and contamination. Various methods can be carried out to improve the properties of biopolymers, one of which is with nanotechnology approaches like incorporating nanofillers.²²

Nanofillers could improve biopolymer properties through better mechanical and barrier properties. Nanofillers also enhance the hydrophobicity and melting temperature of biopolymers. Nanofillers, especially nanoclay, also have been known to have the ability to improve the barrier properties of bionanocomposites. Nanoclay creates a longer diffusion pathway to delay the transfer of molecules, improving barrier properties. Montmorillonite (MMT) is a widely used nanoclay in food packaging applications. Using MMT in a carrageenan film can improve the physical and mechanical properties of the film

by increasing the tensile strength value. The addition of 5% MMT can also improve barrier properties by lowering the permeability of the carrageenan biopolymer film.²²

Antimicrobial nanocomposite packaging systems are particularly effective in gaining these capabilities because of the high surface-to-volume ratio and enhanced surface reactivity of nanosized antimicrobial agents, which are highly useful in preventing microbial contamination for extending shelf life and securing food safety. There are several antimicrobial agents, one of which is inorganic such as nanoparticles. Nanoparticles are considered to be incorporated into biopolymers to form antimicrobial packaging systems. Silver nanoparticles (AgNPs) have been known as inorganic antimicrobial agents due to their unique properties and low toxicity. A study by Rhim and Wang in 2014 reported that nanocomposites incorporated by AgNPs have a great antimicrobial effect against Gram-negative bacteria (*Escherichia coli*). However, AgNPs also have a toxic effect on various fungi, including *Aspergillus*, *Saccharomyces*, and *Candida*. Another inorganic material that has an antimicrobial effect is cerium oxide nanoparticles (CeNPs). CeNPs have an antimicrobial effect on Gram-negative and Gram-positive bacteria. So far, CeNPs have been produced and applied to various technologies, but there has yet to be a report on producing a biopolymer-based nanocomposite film using CeNPs.²²

Extraction of Green Seaweed Polysaccharides:

The extraction of ulvan (the most well-known polysaccharide from green algae) has recently been reviewed, and hence only a brief summary is included here. In accordance with the data found for other seaweed polysaccharide extractions, the quantitative yield was shown to vary significantly, ranging from 2.7–40% of the dry weight (expressed as median% of algal dry weight), and was dependent on both the applied process and the source of biomass.⁴¹

CONCLUSION

Seaweed-derived bioplastics represent a compelling, renewable alternative to petroleum-based plastics, leveraging the abundant polysaccharides alginate, agar, and carrageenan found in brown and red macroalgae. Over the past decade (2010–2025), advances in green extraction techniques and fabrication processes such as solution casting, extrusion, and nanocomposite blending have significantly improved the mechanical integrity and biodegradation profiles of these materials. Alginate-based films with tensile strengths up to 38 MPa and carrageenan blends offering enhanced transparency demonstrate that tailored biopolymer formulations can meet diverse application requirements in packaging, agriculture, and biomedical devices.¹⁷

Despite their promise, seaweed bioplastics face hurdles including elevated production costs, water sensitivity, and variability in biomass supply. Addressing these challenges through strategic polymer blending, incorporation of nanofillers, and optimization of ocean aquaculture practices will be essential to achieve economic viability at scale. Moreover, comprehensive life-cycle and techno-economic assessments are needed to validate the true environmental benefits. With coordinated efforts across research, industry, and policy spanning standardization, supply-chain development, and substrate valorization seaweed-based plastics have the potential to play a pivotal role in a circular, low-carbon economy and substantially mitigate the global plastic crisis.¹⁶

REFERENCES

1. Janani R, Rajesh GM. Production and evaluation of a seaweed-based bioplastic sheet

- for food packaging. *Uttar Pradesh J Zool.* 2024;45:108–15.
2. Sudhakar MP. Studies on the development and characterization of bioplastic film from the red seaweed (*Kappaphycus alvarezii*). *Environ Sci Pollut Res.* 2021;28.
3. Kumar KS. Seaweeds: distribution, production and uses. 2018.
4. Bamaniya K, Joshi N, Tiwari A, Shaji S. Seaweed – classification, source and uses. 2022;2:54–7.
5. Rathod SG, Choudhari AN, Mantri VA. A global bibliometric analysis of seaweed biodiversity, endemic taxa, and conservation (1992–2023). *Phycology.* 2025;5(1):1.
6. Janani R, Rajesh GM. Production and evaluation of a seaweed-based bioplastic sheet for food packaging. *Uttar Pradesh J Zool.* 2024;45:108–15.
7. Chopin, Thierry. (1986). The red alga *Chondrus crispus* Stackhouse (Irish moss) and carrageenans - A review. *Can. Tech. Rep. Fish. Aquat. Sci.* 1514
8. Sudhakar MP, Peter DM, Dharani G. Studies on the development and characterization of bioplastic film from the red seaweed (*Kappaphycus alvarezii*). *Environ Sci Pollut Res Int.* 2021 Jul; 28(26): 33899–913.
9. El-Sheekh MM, Alwaleed EA, Ibrahim A, Saber H. Preparation and characterization of bioplastic film from the green seaweed *Halimeda opuntia*. *Int J Biol Macromol.* 2024;259(Pt 2):129307.
10. Dang BT, Bui XT, Tran DPH, et al. Current application of algae derivatives for bioplastic production: a review. *Bioresour Technol.* 2022;347:126698.
11. Perera KY, Sharma S, Pradhan D, Jaiswal AK, Jaiswal S. Seaweed polysaccharide in food contact materials (active packaging, intelligent packaging, edible films, and coatings). *Foods.* 2021; 10(9):2088.
12. Kajla P, Chaudhary V, Dewan A, et al. Seaweed-based biopolymers for food packaging: a sustainable approach for a cleaner tomorrow. *Int J Biol Macromol.* 2024; 274(Pt 1):133166.
13. Santana I, Félix M, Guerrero A, Bengoechea C. Processing and characterization of bioplastics from the invasive seaweed *Rugulopterix okamurae*. *Polymers (Basel).* 2022; 14(2):355.
14. Mohammed A, Gaduan A, Chaitram P, Pooran A, Lee KY, Ward K. Sargassum inspired, optimized calcium alginate bioplastic composites for food packaging. *Food Hydrocolloids.* 2023 Feb 1; 135:108192.

15. de Mello Soares CT, Ek M, Östmark E, Gällstedt M, Karlsson S. Recycling of multi-material multilayer plastic packaging: Current trends and future scenarios. *Resources, conservation and recycling*. 2022 Jan 1; 176:105905.
16. Mohammed A, Ward K, Lee KY, Dupont V. The environmental impact and economic feasibility assessment of composite calcium alginate bioplastics derived from *Sargassum*. *Green Chemistry*. 2023; 25(14):5501-16.
17. Kan M, Miller SA. Environmental impacts of plastic packaging of food products. *Resources, Conservation and Recycling*. 2022 May 1; 180:106156.
18. Gade R, Tulasi MS, Bhai VA. Seaweeds: a novel biomaterial. *Int J Pharm Pharm Sci*. 2013;5(2):975-1491.
19. Santana I, Felix M, Bengoechea C. Seaweed as basis of eco-sustainable plastic materials: focus on alginate. *Polymers (Basel)*. 2024;16(12):1662.
20. Torrejon VM, Fernando S, Roy UK, Onwukwe U, Anguilano L. Transforming seaweed into bioplastics: a review of cultivation, harvesting and processing methods. *Appl Phycology*. 2025;6(1):52-73.
21. Janani R, Rajesh GM. Production and evaluation of a seaweed-based bioplastic sheet for food packaging. *Uttar Pradesh J Zool*. 2024;45:108-15.
22. Genecya G, Adhika DR, Sutrisno W, Wungu TD. Characteristic improvement of a carrageenan-based bionanocomposite polymer film containing montmorillonite as food packaging through the addition of silver and cerium oxide nanoparticles. *ACS omega*. 2023 Oct 12;8(42):39194-202.
23. Rathod SG, Choudhari AN, Mantri VA. A global bibliometric analysis of seaweed biodiversity, endemic taxa, and conservation (1992-2023). *Phycology*. 2025;5(1):1.
24. Ryan C, Billington S, Criddle C. Biocomposite fiber-matrix treatments that enhance in-service performance can also accelerate end-of-life fragmentation and anaerobic biodegradation to methane. *J Polym Environ*. 2018;26:10.
25. Ahsan WA, Hussain A, Lin C, Nguyen MK. Biodegradation of different types of bioplastics through composting—a recent trend in green recycling. *Catalysts*. 2023;13(2):294.
26. Miwa, Y., Awanthi, M. G. G., Soga, K., Tanaka, A., Ito, M., Numata, Y., Sato, Y., & Konishi, T. (2023). The Cell Wall Characterization of Brown Alga *Cladosiphon okamuranus* during Growth. *Plants*, 12(18), 3274.
27. Dobrinčić, A., Balbino, S., Zorić, Z., Pedisić, S., Bursać Kovačević, D., Elez Garofulić, I., & Dragović-Uzelac, V. (2020). Advanced Technologies for the Extraction of Marine Brown Algal Polysaccharides. *Marine drugs*, 18(3), 168.
28. Polman EM, Gruter G-JM, Parsons JR, Tietema A. Comparison of the aerobic biodegradation of biopolymers and the corresponding bioplastics: A review. *Sci Total Environ*. 2021;753:141953.
29. Koch D, Mihalyi B. Assessing the change in environmental impact categories when replacing conventional plastic with bioplastic in chosen application fields. *Chem Eng Trans*. 2018;70:853-8.
30. Huang J, Veksha A, Chan WP, Giannis A, Lisak G. Chemical recycling of plastic waste for sustainable material management: A prospective review on catalysts and processes. *Renew Sustain Energy Rev*. 2022;154:111866.
31. Mellinas C, Valdés A, Ramos M, Burgos N, Garrigos MC, Jiménez A. Active edible films: Current state and future trends. *J Appl Polym Sci*. 2016;133.
32. Mekonnen T, Mussone P, Khalil H, Bressler D. Progress in bio-based plastics and plasticizing modifications. *J Mater Chem A*. 2013; 1:13379-98.
33. Suman TY, Li W-G, Alif S, Faris VRP, Amarnath DJ, Ma J-G, *et al*. Characterization of petroleum-based plastics and their absorbed trace metals from the sediments of the Marina Beach in Chennai, India. *Environ Sci Eur*. 2020;32:110.
34. Quitain AT, Kai T, Sasaki M, Goto M. Microwave-hydrothermal extraction and degradation of fucoidan from supercritical carbon dioxide deoiled *Undaria pinnatifida*. *Industrial & engineering chemistry research*. 2013 Jun 12;52(23):7940-6.
35. Chae Y, An Y-J. Current research trends on plastic pollution and ecological impacts on the soil ecosystem: A review. *Environ Pollut*. 2018;240:387-95.
36. Burgos N, Valdés A, Jiménez A. Valorization of agricultural wastes for the production of protein-based biopolymers. *J Renew Mater*. 2016;4:165-77.
37. Abdul Khalil HPS, Tye YY, Saurabh CK, Leh CP, Lai TK, Chong EWN, Nurul Fazita MR, Hafiidz JM, Banerjee A, Syakir MI. Biodegradable polymer films from seaweed polysaccharides: A review on cellulose as a reinforcement material. *Express Polym Lett*.

- 2017;11(4):244–265.
38. Júnior J, Turan G. Biodegradable plastic and film production from seaweeds. *Bull Biotechnol.* 2022;3.
39. Wan Yahaya WA, Azman NAM, Adam F, Subramaniam SD, Abd Hamid KH, Almajano MP. Exploring the potential of seaweed derivatives for the development of biodegradable plastics: A comparative study. *Polymers (Basel).* 2023; 15(13):2884.
40. Sacramento MMÂ, Borges J, Correia FJS, Calado R, Rodrigues JMM, Patrício SG, Mano JF. Green approaches for extraction, chemical modification and processing of marine polysaccharides for biomedical applications. *Frontiers in Bioengineering and Biotechnology.* 2022; 10:1041102
41. Xu, J., Liao, W., Liu, Y., Guo, Y., Jiang, S., & Zhao, C. (2023). An overview on the nutritional and bioactive components of green seaweeds. *Food production, processing and nutrition,* 5(1), 18.
42. Jönsson, Madeleine & Allahgholi, Leila & Sardari, Roya & Hreggvidsson, Gudmundur & Karlsson, Eva. (2020). Extraction and Modification of Macroalgal Polysaccharides for Current and Next-Generation Applications. *Molecules.* 25.930.10.3390/molecules25040930.
43. Jönsson M, Allahgholi L, Sardari RRR, Hreggviðsson GO, Nordberg Karlsson E. Extraction and modification of macroalgal polysaccharides for current and next-generation applications. *Molecules.* 2020;25(4):930.
44. Sacramento MMÂ, Borges J, Correia FJS, Calado R, Rodrigues JMM, Patrício SG, Mano JF. Green approaches for extraction, chemical modification and processing of marine polysaccharides for biomedical applications. *Front Bioeng Biotechnol.* 2022;10:1041102.