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Comprehensive review of alginate: Sources, synthesis, and application in the food packaging sector

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REVIEW ARTICLE

Abstract

Alginate, a natural biopolymer sourced primarily from seaweed and microbial origins, has garnered increased attention for its adaptability, biodegradability, and sustainability, making it a valuable material for food packaging applications. This review provides an in-depth examination of the current advancements in alginate, including its sources, extraction techniques, synthesis methods, and diverse applications within the food packaging industry. The review will detail various alginate extraction methods, along with modifications, including chemical functionalization and nanotechnology integration. Key applications of alginate, such as films, coatings, blends, and composites, are analyzed, emphasizing their biodegradability, mechanical strength, and barrier properties, which contribute to reducing environmental impact, with details also displayed. Additionally, this review underscores alginate's potential to transform the food packaging industry into a sustainable alternative to conventional plastics, addressing critical environmental challenges. The existing limitations, which create the need for ongoing research and innovation to overcome these barriers and expand the industrial applications of alginate, are also discussed here.

Keywords: alginate; biopolymer; extraction; feedstocks; food packaging; synthesis

Introduction

The food packaging industry is increasingly challenged to meet environmental sustainability and regulatory standards due to its dependence on plastic materials. While plastics are affordable and versatile, their nonbiodegradability and inefficient recycling systems contribute to significant environmental pollution and carbon emissions (Verma *et al.*, 2024), with existing recycling efforts hindered by low recovery rates and contamination (Munoz-Briones *et al.*, 2024).

Bioplastics, derived from renewable sources such as corn and sugarcane, offer a biodegradable alternative to conventional plastics. However, their widespread adoption is hindered by high production costs and performance limitations. Furthermore, recent advancements in converting food waste into packaging materials show promise but require additional research to enhance their material properties, quality, and cost-effectiveness to become viable alternatives (Khandeparkar *et al.*, 2024; Yildiz and Öztekin, 2024).

One of the materials being explored for bioplastic synthesis is alginate, a natural polysaccharide primarily extracted from the cell walls of brown algae (Phaeophyceae). Alginate was first discovered by British chemist E.C.C. Stanford in 1881. It is composed of two monomeric units, β-D-mannuronic acid (M) and α-L-guluronic acid (G), which are connected by 1→4 glycosidic bonds. These monomers are abundantly found in brown algae species such as *Laminaria*, *Macrocystis*, and *Ascophyllum* (Bertagnolli *et al.*, 2014; Garcia-Vaquero *et al.*, 2017). In addition to brown algae, certain bacteria, including *Azotobacter vinelandii* and *Pseudomonas* species, also yield alginates (Ertesvåg *et al.*, 1995; Rehm *et al.*, 1994).

Alginates are primarily valued for their gelling, thickening, and stabilizing properties, making them highly useful in the food and pharmaceutical industries. In food applications, they act as texture modifiers, stabilizers, and emulsifiers, enhancing the consistency and quality of products. Similarly, in pharmaceuticals, alginates are used to control the viscosity and stability of formulations, contributing to their effectiveness and usability (Freitas *et al.*, 2011; Gheorghita Puscaselu *et al.*, 2020). Currently, the global commercial production of alginate is estimated to be around 30,000 metric tons per year. The majority of this production is concentrated in six key countries: China, the USA, the UK, Japan, Chile, and Germany (Rehm *et al.*, 1994). Alginate possesses a unique combination of physicochemical properties that make it highly valuable for diverse industrial applications. It is biocompatible, nontoxic, biodegradable, and capable of forming stable gels when combined with divalent ions like calcium. These characteristics have led to its widespread use in various sectors as mentioned previously (Ahmed, 2019). Alginate's unique ability to form viscous films and gels, even at low concentrations, makes it highly effective as a thickener and stabilizer in food applications (Benjamin *et al.*, 2018). By adjusting the ratio of its β-D-mannuronic acid (M) and α-L-guluronic acid (G) blocks, alginates can be customized to exhibit specific properties, such as enhanced mechanical strength or improved control over moisture and gas permeability. This adaptability further expands its utility in various industrial applications (Aarstad *et al.*, 2012).

The rigidity and brittleness of pure alginate films pose significant challenges for their practical application. To address these limitations, the incorporation of plasticizers or other additives is essential. These additives lower the glass transition temperature (Tg) of alginate, improving its flexibility and stretchability. These enhanced properties are crucial for making alginate films more suitable for effective food packaging applications (Edgar, 2007; Tong *et al.*, 2023). Alginate films can be enhanced by incorporating antimicrobial compounds, antioxidants, and active agents, which help extend the shelf life of food and ensure its safety. These additives can provide additional functional properties, such as inhibiting microbial growth, preventing oxidation, and maintaining the quality of packaged food products. This makes alginate films a versatile and effective option for active food packaging applications (Gheorghita Puscaselu *et al.*, 2020). Besides this, alginate is also prominently utilized in the biomedical field for applications such as wound healing, controlled drug delivery, and tissue engineering. Its widespread use is attributed to its excellent biocompatibility and unique ability to form three-dimensional gel structures (Rhein-Knudsen et al., 2015), which create an ideal environment for cell encapsulation, controlled release of therapeutic agents, and tissue regeneration. These characteristics position alginate as a versatile and valuable biomaterial in advancing therapeutic and regenerative medicine.

The previous studies and available data highlight the significance of alginate as a versatile and highly promising material for a wide range of applications. However, despite extensive research, the information on alginate remains scattered across various sources, creating a need for a comprehensive review that consolidates and systematically analyzes existing knowledge. Such an effort would enhance clarity, facilitate further advancements, and provide a solid foundation for future research and practical applications.

To this end, the following review provides a comprehensive analysis of the sources, synthesis methods, and applications of alginate in food packaging. It systematically summarizes its key advantages and practical applications while highlighting recent advancements in the extraction, modification, and utilization of alginate films. Emphasizing their potential to mitigate the environmental impact of conventional packaging materials, the review also examines the technical and economic challenges associated with large-scale implementation. Furthermore, it explores future research directions, including the optimization of formulations and the integration of emerging technologies to enhance the functional properties and commercial viability of alginate-based packaging materials.

Alginate Feedstock Sources

Natural sources

Seaweed

Alginate is predominantly extracted from brown seaweed species across various coastal regions worldwide. Brown algae constitute the primary source of alginate due to their high yield and widespread availability.

These macroalgae thrive in diverse marine environments, from the warm waters of the Persian Gulf to the temperate coasts of Europe and the tropical regions of the Caribbean and Southeast Asia. Each species of seaweed contributes differently to alginate production, offering varying yields due to differences in their structure. This highlights the importance of selecting the right species for specific purposes and refining extraction methods to maximize both the quantity and quality of alginate. One such species is *Sargassum muticum*, commonly harvested from locations such as Praia da Mourisca in Pontevedra, Spain, where studies have shown that using ultrasound-assisted extraction methods with this seaweed results in high alginate yields (Flórez-Fernández *et al.*, 2019). Also, *Sargassum vulgare* specimens collected from Pacheco Beach yielded alginates with a concentration of 16.9% (Torres *et al.*, 2007). Another notable collection point is the Lebanese Mediterranean coast, where *S. vulgare* showed a high yield of 40.0% (Sari-Chmayssem *et al.*, 2016).

Seaweed harvesting methods include manual collection during low tide, as observed in species such as *Sargassum aquifolium, Padina australis,* and *Turbinaria ornata* in Bali, as well as mechanical harvesting from cultivated farms or wild populations. Sustainable practices are essential to maintaining ecological balance and ensuring a stable alginate supply. This requires careful management of seaweed populations and the use of techniques that minimize environmental impact while maximizing yield. Harvesting methods and corresponding yields for other species are summarized in Table 1.

Microbial sources

Microbes are cultivated under regulated conditions which allow for increased alginate synthesis, leading to various advantages over traditional seaweed extraction techniques. Higher yields and improved consistency are among the benefits, making alginate production a sustainable and scalable solution. Microbes such as *Azotobacter vinelandii* have demonstrated significant potential for generating alginate from various carbon sources. Under ideal conditions, such as mannitol as a carbon source and low phosphate levels, alginate yields can reach up to 4.5 g/L (Bonartseva *et al.*, 2017). Moreover, alginate production with *A. vinelandii* can vary depending on the cultivation conditions, ranging from 3.5 to 4.67 g/L based on the carbon source used (Kıvılcımdan Moral and Yıldız, 2016). This adaptability in culture conditions allows for tailored production to meet specific needs while offering a cost-effective alternative to seaweed-based methods, which often have negative environmental impacts. *Pseudomonas aeruginosa* and other Pseudomonas strains have also been investigated for their alginate production capabilities. Among the strains tested, *P. aeruginosa* exhibited the highest alginate production, reaching 177.2 mg/g (Jimoh *et al.*, 2024). In contrast, other strains such as *Pseudomonas nitroreducens* showed more modest yields, ranging from 8.7 to 24.3 mg/g (Zhang *et al.*, 2022).

Extraction methods

Mechanical processing

Mechanical processing involves grinding and sieving to remove alginate from biomass. The success of this treatment is determined by the degree of cell wall breakdown and alginate release. High-pressure homogenization and ultrasound are employed to increase extraction efficiency. The first step is to mechanically reduce the size of the algae. After harvesting, the dried seaweed biomass

Table 1. Alginate yields from various seaweed species across different geographic locations.

Seaweed species	Location	Alginate yield (%)	Harvesting method	Reference
Sargassum fluitans	Guanabo Beach, Havana	21.1–24.5%	Manual collection	Davis *et al.* (2004)
Sargassum oligocystum	Great Barrier Reef, Australia	16.3–20.5%	Manual collection	Davis *et al.* (2004)
Sargassum angustifolium	Persian Gulf	24.4% (summer), 22.4% (winter)	Manual collection	Ardalan *et al.* (2018)
Nizimuddinia zanardini	Iran	24.0%	Manual collection	Khajouei *et al.* (2018)
Sargassum turbinarioides	Madagascar	10.0%	Manual collection	Fenoradosoa *et al.* (2010)
Sargassum latifolium	Red Sea region, Egypt	17.7%	Manual collection	Larsen *et al.* (2003)
Sargassum filipendula	Brazil	15.1–17.2%	Manual collection	Freitas *et al.* (2011)
Turbinaria triquetra	Red Sea, Hurghada, Egypt	22.2%	Manual collection	Rashedy *et al.* (2021)
Hormophysa cuneiformis	Red Sea, Hurghada, Egypt	13.3%	Manual collection	Rashedy *et al.* (2021)
Sargassum muticum	Northeastern Coast, Algeria	17.4%	Mechanical and manual collection	Bouzenad *et al.* (2024b)
Dictyota dichotoma	Northeastern Coast, Algeria	14.5%	Mechanical and manual collection	Bouzenad *et al.* (2024b)

is chopped into small pieces and processed. These are pulverized into powders with particle sizes of around 0.5 mm, which increases interaction with solvents and chemicals and thereby improves extraction efficiency (Saji *et al.*, 2022). This method can be performed via different approaches as highlighted in Figure 1.

Studies have shown that the particle size significantly impacts extraction yield. For instance, in a study on alginate extraction from *Laminaria digitata*, samples were cut into two particle sizes: below 1 mm and between 1 and 5 mm. The highest yield of 51.8% was achieved for samples smaller than 1 mm at 40°C (Fertah *et al.*, 2017). Another study of alginate extraction from *Durvillaea potatorum*, harvested at Rivoli Bay, Beachport, South Australia, involved grinding the algae into a fine powder using a 250 μm sieve, resulting in a yield of 13.32% acid-extractable and 23.23% alkali-extractable alginate (Abraham *et al.*, 2019). Algae with particle sizes between 0.25 and 1 mm are commonly used in laboratory research (Zhang *et al.*, 2022). The reduction in particle size can increase extraction yield, but it may increase energy consumption and make the process less economical. Particle size and mechanical pretreatment are crucial for improving alginate extraction efficiency and yield. By reducing algae to smaller particles, extraction surface area increases, facilitating better interaction with extractants and higher yields.

Chemical extraction

Chemical extraction is a popular method for extracting alginate from seaweed, using alkaline solutions like sodium carbonate (Na_2CO_3) to break down cell walls and release alginate as described in Figure 2. This method is efficient and adaptable, allowing for the optimization of parameters to maximize yield and purity. It involves acid and alkaline treatments to solubilize alginate and remove impurities. The following studies presented in Table 2 illustrate the effectiveness of chemical extraction methods.

The studies reveal that combining acid pretreatment with alkaline solutions, such as Na_2CO_3, enhances the breakdown of seaweed cell walls, leading to high alginate yields with varying purity and functional properties. Key parameters such as acid and alkali concentrations, temperature, and extraction time are critical for improving extraction efficiency. As mentioned in Table 2, *Durvillaea potatorum* yielded 43.57% polysaccharides under optimized conditions, while *L. digitata* achieved 51.8% at 40°C. Multistage extraction with *Sargassum natans* boosted yields to 28.16%, and hot extraction with *Sargassum siliquosum* yielded 49.9%. The results reveal that chemical extraction is highly successful for alginate manufacture; nevertheless, regulating extraction conditions such as acid and alkali concentrations, temperature, and duration is critical for enhancing yield and functional characteristics. By fine-tuning these parameters, alginate can be manufactured with improved properties, making it ideal for a wide range of applications, including biomedical and industrial.

Enzymatic extraction

Enzymatic extraction has emerged as a promising alternative to conventional methods for isolating alginate from seaweeds. This approach utilizes specific enzymes

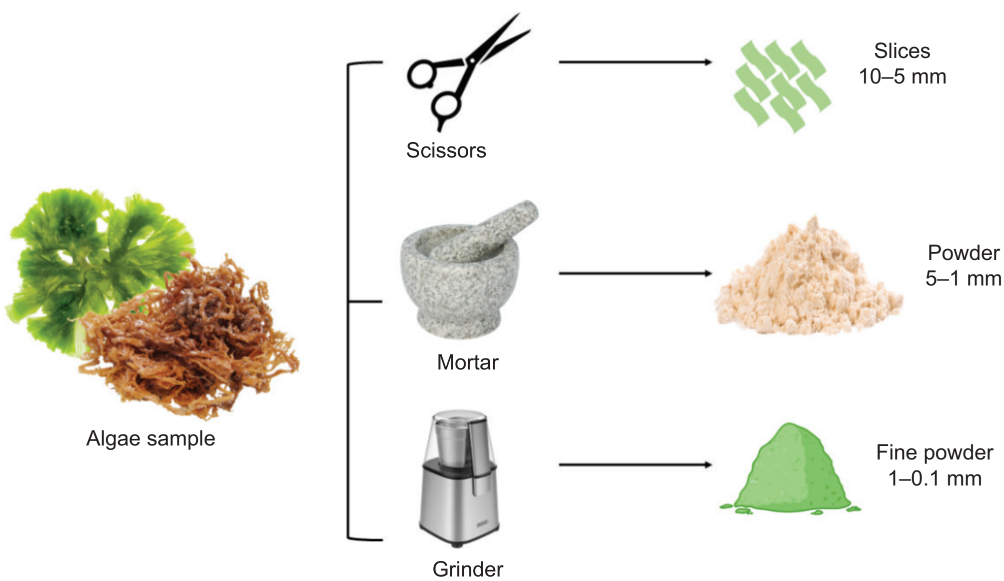

Figure 1. Mechanical processing approaches for alginate.

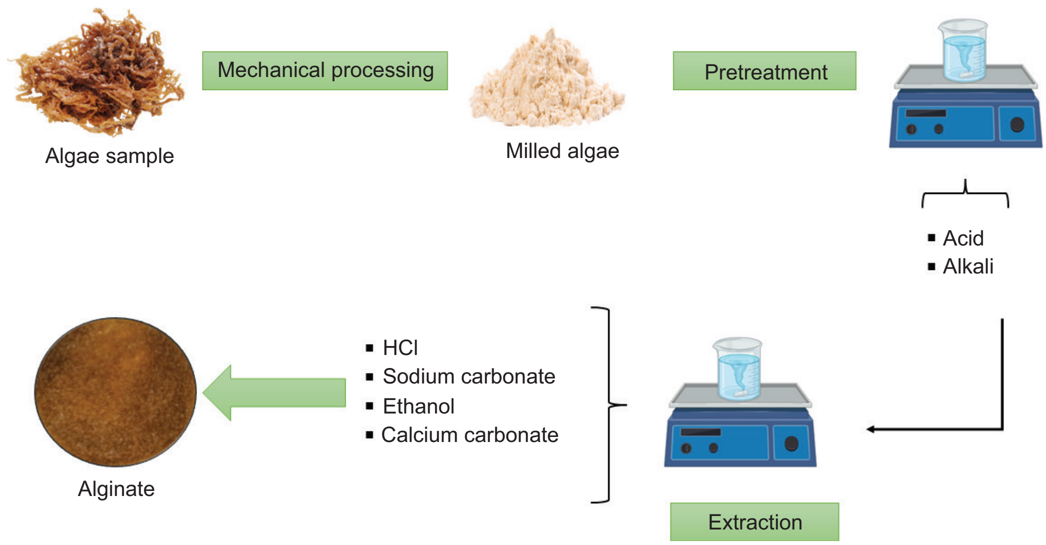

Figure 2. Chemical extraction method for alginate.

Table 2. Alginate yields from various seaweed species utilizing chemical extraction.

Seaweed species	Location	Extraction process	Optimal conditions	Yield	Reference
Durvillaea potatorum	–	Acidic (HCl) and Alkaline (Na_2CO_3)	0.05 M HCl at 60°C for 3 h	43.57% (Polysaccharides), 23.23% (Alginate)	Abraham et al. (2019)
Sargassum muticum	Nykøbing Mors, Denmark	Na_2CO_3 (RSM Method)	3% Na_2CO_3 at 86°C	13.57%	Mazumder et al. (2016)
Laminaria digitata	Moroccan Atlantic coast	Na_2CO_3 (Under agitation for 5 h)	40°C	51.8%	Fertah et al. (2017)
Sargassum polycystum	–	Na_2CO_3 and EDTA (Treatment 1)	7.0% Na_2CO_3	41.08%	Yudiati et al. (2018)
Sargassum natans	Caribbean waters	Multistage extraction (H_2SO_4, Na_2CO_3)	5% Na_2CO_3, 65°C, 2 h, 1:15 volume ratio	28.16% (Two-stage cumulative yield)	Mohammed et al. (2018)
Sargassum vulgare	Brazilian coastal waters	Formaldehyde, HCl pretreatment, Na_2CO_3 extraction	60°C for 5 h	16.9%	Torres et al. (2007)
Sargassum baccularia, S. binderi, S. siliquosum, Turbinaria conoides	Port Dickson, Malaysia	Hot and cold extraction methods	Hot method (50°C for 3 h)	49.9% (*Sargassum siliquosum*), 41.4% (*Trochomorpha conoides*)	Chee et al. (2011)

to selectively degrade cell walls and release target biomolecules under mild conditions. Unlike chemical extraction, which often involves harsh reagents and high temperatures that can degrade functional properties, enzymatic extraction preserves the integrity and bioactivity of the extracted compounds. For instance, the enzymatic extraction of fucoidan and alginate from *Ecklonia radiata*, collected from the Australian coast, employed cellulases and hemicellulases in a sequential process, extracting fucoidan first, followed by alginate. This method improved yield and purity while maintaining alginate's functional properties due to its gentle nature. The findings highlight enzymatic extraction as a more sustainable alternative, offering higher purity and reduced environmental impact compared to traditional chemical methods (Lorbeer *et al.*, 2015). *S. muticum*, seaweed collected from the Spanish coast, was treated with specific enzymes under mild conditions. This approach significantly improved yield and produced high-purity alginate while preserving its structural integrity and functional properties. The findings highlight the advantages of enzymatic extraction for high-value applications, demonstrating its potential for producing high-quality alginate (Flórez-Fernández *et al.*, 2019).

The success of enzymatic extraction in *E. radiata* and *S. muticum* highlights its potential as a sustainable method, reducing environmental impact while yielding high-quality alginate for industrial applications. This approach supports greener and more efficient marine biomass valorization.

Ultrasound-assisted extraction

Ultrasound-assisted extraction (UAE) is an efficient and eco-friendly method for extracting alginate, offering advantages over traditional acid and alkaline methods. It has also proven valuable in extracting bioactives from plant sources, as demonstrated by Wang *et al.* (2025), reinforcing its versatility. By using ultrasonic waves to break cell walls, UAE enhances alginate release under mild conditions, reducing extraction time and energy consumption while preserving functional properties, which is demonstrated in Figure 3. This method shows its efficiency across various studies. *S. muticum* from the Spanish coast, UAE at 25°C for 5–30 min increased alginate yields linearly, reaching 15% after 30 min. The extracted alginate exhibited stable, thermo-reversible properties, confirming UAE as a sustainable and effective extraction technique with broad applicability (Flórez-Fernández *et al.*, 2019). *Fucus vesiculosus* was employed to extract alginate using the UAE through sodium bicarbonate as a solvent, optimizing parameters to maximize yield and efficiency. The seaweed, a byproduct of fucoidan extraction, showcased the potential of UAE for utilizing residual biomass. Response surface methodology (RSM) optimized ultrasound amplitude (19.64–91%) and extraction time (6–34 min) at 20 kHz, identifying 69% amplitude and 30 min as ideal conditions. This process produced low-molecular-weight alginate while significantly improving efficiency, and reducing extraction time and energy consumption compared to conventional methods (Ummat *et al.*, 2024).

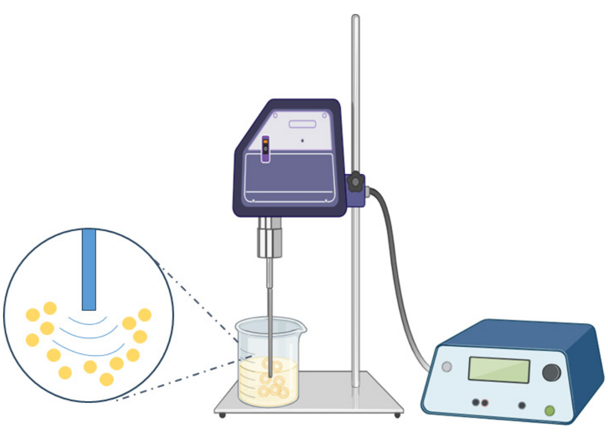

Figure 3. Ultrasound-assisted extraction technique used for alginate.

Studies on UAE of alginate from *S. muticum* and *F. vesiculosus* demonstrate its superiority over conventional methods. UAE significantly improves alginate yield while reducing extraction time and energy consumption, making it a more sustainable and efficient alternative. Recent reviews emphasize the growing role of UAE in sustainable extraction of food-grade polymers and additives (Pereira *et al.*, 2025). Optimization of key parameters—including sonication time, ultrasound amplitude, and solvent selection—enhanced extraction efficiency and quality. The resulting alginate exhibited desirable properties such as stability and thermo-reversibility, comparable to traditional methods. Additionally, UAE effectively utilizes residual biomass, highlighting its potential for waste valorization. These findings establish UAE as a green, scalable extraction technique, supporting the transition toward eco-friendly bioprocessing in alginate production.

Microwave-assisted extraction

Microwave-assisted extraction (MAE) is a rapid and energy-efficient technique for extracting alginate from seaweeds, offering superior speed, efficiency, and yield compared to conventional methods. By using microwave radiation to heat the extraction medium, MAE enhances solvent penetration and alginate release while reducing extraction time and energy consumption, which was approved by recent studies as indicated in Table 3.

By optimizing parameters such as temperature, microwave power, and solvent-to-biomass ratio, MAE was shown to achieve high yields of alginate while significantly reducing extraction time and energy consumption compared to traditional methods. Additionally, the combination of MAE with acid pretreatment, as demonstrated in some studies, further enhanced the extraction efficiency and yield, providing a more comprehensive approach to alginate recovery. The success of MAE in preserving the functional properties of alginate and achieving high yields with lower environmental impact supports its potential as a preferred method for alginate extraction in industrial applications. These findings highlight the need for further exploration and optimization of MAE techniques, paving the way for more sustainable and efficient alginate extraction processes from marine biomass.

Synthesis of Alginate

Industrial production

Industrial production of alginate is traditionally associated with the extraction from brown algae; However, in addition to traditional extraction, microbial production of alginate using *A. vinelandii* and *Pseudomonas* species

Table 3. Alginate yields from various seaweed species utilizing microwave-assisted extraction.

Seaweed species	Location	Optimal conditions	Yield	Reference
Undaria pinnatifida	–	67°C, 400 W 29 mL/g ratio, 19 min	31.39%	Nam *et al.* (2024)
Nizimuddinia zanardini	Coastal regions	/	26.4%	Torabi *et al.* (2022)
Saccorhiza polyschides	Portuguese coast	20°C for 14 h with 0.1 M HCl	26.4%	Silva *et al.* (2015)
Sargassum cristaefolium	–	Seaweed/solution ratio of 1:5, 27.5 feed speed rpm, pH =12	45.54%	Sugiono *et al.* (2019)
Sargassum fluitans	–	High-temperature alkaline treatments	24.5%	Davis *et al.* (2004)
Sargassum fluitans	–	High-temperature alkaline treatments	20.5%	Davis *et al.* (2004)

is gaining industrial interest. These bacteria synthesize alginate as an extracellular polymer, and its properties can be tailored by optimizing culture conditions. This biotechnological approach offers a controlled, scalable, and sustainable alternative for industrial alginate production, ensuring consistent quality and supply (Urtuvia *et al.*, 2017). This microbial production is becoming increasingly attractive due to its ability to provide alginates with stable and specific characteristics, while using cheap carbon sources such as carbon-rich industrial waste, thus reducing production costs (Wang *et al.*, 2023). Bacterial strains such as *Pseudomonas fluorescens* offer an opportunity for more sustainable industrial production, thanks to genetic modifications that optimize access to fructose 6-phosphate and energy management, two critical factors in alginate production (Maleki *et al.*, 2017). This approach supports the broader framework of biomass biotransformation into value-added materials, as explored by Chaabouni *et al.* (2014). The valorization of industrial waste generated by alginate production, rich in bioactive compounds such as fucoidans and polyphenols, also offers opportunities to improve the sustainability of industrial practices without altering existing processes (Bojorges *et al.*, 2022). Additionally, the valorization of byproducts rich in bioactive compounds presents opportunities to enhance the sustainability of industrial practices without significant alterations to existing processes. Overall, microbial production of alginate offers a viable path forward for the industrial sector, promoting eco-friendly and cost-effective production methods that support broader efforts in sustainable biopolymer development.

Modification and functionalization

Bacterials alginates differ from those of algae in their degree of acetylation and molecular weight, which can be modified to influence viscosity, flexibility, and gelling properties, making bacterial alginates suitable for a variety of applications such as biomedical materials and food products (Urtuvia *et al.*, 2017). Modification techniques include amidation, sulfation, and esterification, which improve the mechanical and biochemical properties of alginates, making them more versatile for applications such as wound healing and drug delivery (Wang *et al.*, 2023). The regulation of alginate biosynthesis in bacteria involves a complex network of genes and regulations, including sigma and anti-sigma factors, enabling the molecular structure of alginate to be precisely controlled to obtain the desired properties (Hay *et al.*, 2014). In addition, techniques such as cross-linking and grafting can tailor the properties of alginate gels, improving their uniformity and performance in specific applications (Fertah *et al.*, 2017). Such functionalization strategies are consistent with innovations in hydrophobic polymer design from food waste, as noted by Sanchez-Vazquez *et al.* (2013). These innovations in alginate modification not only broaden the scope of potential uses but also underscore the versatility of bacterial alginates as a valuable resource in the development of sustainable, high-performance biopolymers.

Nanotechnology integration

Bacterial alginates offer unique advantages when combined with nanotechnologies, forming nanocomposites that enhance their mechanical strength and barrier properties. These nanocomposites have potential applications in food packaging and medical devices, offering improved preservation and protection against environmental factors (Bonartseva *et al.*, 2017). Alginate gels and nanogels, produced by innovative techniques such as templating with nanovesicles, are particularly suited for advanced applications such as targeted drug delivery and tissue engineering, where their small size and specific surface area are crucial assets (Ching *et al.*, 2017).

The production of alginate by attenuated bacterial strains, such as *P. aeruginosa PGN5*, makes it possible to create tailor-made materials for nanotechnologies, while reducing the risks associated with pathogenicity and optimizing the physicochemical properties of alginate for specific applications (Valentine *et al.*, 2020). Finally, the ability to visualize alginate biosynthetic complexes using advanced techniques such as immunogold labeling enables us to better understand and improve production processes at the molecular scale, paving the way for even more specialized applications of alginate nanocomposites (Maleki *et al.*, 2017). This section highlights the growing importance of bacterial alginates in industrial and biomedical applications, thanks to their production flexibility, scalable properties, and potential in advanced technologies such as nanocomposites. Waste recovery strategies, chemical and physical modification techniques, and the integration of nanotechnologies are all promising avenues for diversifying and enriching alginate applications, while meeting today's environmental and economic challenges.

Applications of Alginate in Food Packaging

Properties of alginate relevant to food packaging

Alginate is widely recognized for its biodegradability and environmental benefits, making it a promising alternative to conventional plastic packaging. Its functional integration into packaging systems is consistent with processing constraints and opportunities described by Lewis and Grandison (2011). Alginate films, derived from natural sources like brown algae, decompose naturally and are nontoxic, thus offering a sustainable solution that aligns with the industry's shift toward eco-friendly materials. For instance, films developed from *S. muticum* alginate and sodium alginate (Bouzenad *et al.*, 2024a), as well as those blended with hydrolyzed collagen (Azucena Castro-Yobal *et al.*, 2021), babassu coconut mesocarp (Rashedy *et al.*, 2021), and other biopolymers (Marangoni Júnior *et al.*, 2021), exhibit significant biodegradability, reducing the environmental impact compared to traditional plastics. As highlighted by Taktak *et al.* (2025), such biopolymers represent viable candidates in the ongoing shift toward safer, renewable food contact materials. Additionally, alginate-based films made from a blend with agar and enriched with additives such as stevia or grapefruit seed extract also provide enhanced biodegradability and active biofunctionalities, making them suitable for food packaging applications (Amariei *et al.*, 2022; Gheorghita Puscaselu *et al.*, 2020; Wang and Rhim, 2015). These alginate-based films also demonstrate excellent barrier properties against moisture, oxygen, and light, which are crucial for preserving food quality. Modifications through cross-linking, incorporation of natural additives, or nanocomposites like Au-TiO_2, have been shown to significantly improve these barrier properties. For example, the incorporation of protein hydrolysates into alginate films enhances water vapor permeability and barrier properties against visible light, which is essential for protecting light-sensitive foods (de Oliveira Filho *et al.*, 2019). Table 4 presents a summary of the functional properties, advantages, and limitations of alginate films for food packaging, according to various formulations and alginate sources. Similarly, the incorporation of citric acid and plasma-activated water (PAW) into alginate films has demonstrated a 44% reduction in water vapor transmission rate, enhancing moisture retention crucial for food preservation (Sharmin *et al.*, 2021b).This improvement is primarily due to the action of reactive oxygen and nitrogen species (RONS) generated in PAW, which modify the alginate matrix through increased cross-linking and microstructural reorganization. These physicochemical changes lead to enhanced barrier efficiency, thermal resistance, and mechanical stability, making PAW-modified films particularly attractive for active food packaging applications (Dysjaland *et al.*, 2022; Sharmin *et al.*, 2021a). Furthermore, blends with tannic acid have been noted for their enhanced UV-blocking capabilities and antimicrobial functions, further extending the potential applications of alginate films in packaging (Li *et al.*, 2022). Mechanical properties of alginate films are crucial for applications requiring durability and flexibility. Cross-linking agents such as calcium chloride, plasticizers, and natural additives such as castor oil enhance tensile strength and flexibility. For example, incorporating babassu coconut mesocarp and glycerol improved tensile strength and reduced brittleness, making the films suitable for flexible packaging (Lopes *et al.*, 2020). Alginate films plasticized with hydrophilic and hydrophobic agents showed varying mechanical strengths, offering customization based on packaging needs (Paixão *et al.*, 2019). Additionally, films containing collagen have shown improved structural integrity and thermal stability, making them robust choices for packaging applications (Wang and Rhim, 2015). Alginate-based films are a sustainable alternative to conventional plastic packaging due to their biodegradability, environmental benefits, and functional properties. Such biodegradable polymers have long been recognized for their potential in edible film applications, as highlighted by Cruz-Romero and Kerry (2009), who emphasized the importance of optimizing film formulation to overcome water sensitivity and mechanical limitations. They offer natural barrier protection against moisture, oxygen, and light, helping preserve food quality. Modifications such as cross-linking, natural additives, and nanocomposites further enhance these properties. Additionally, their mechanical strength and flexibility can be tailored for various packaging applications.

Alginate-based films and coatings

Alginate films possess strong film-forming properties, making them versatile materials for developing coatings

Table 4. Overview of alginate film properties and limitations for food packaging.

Seaweed species	Location	Formulation/Additive	Advantages	Limitations	Reference
Sargassum muticum	Northeastern Coast, Algeria	*Sargassum muticum* alginate	Eco-friendly, renewable	Brittle without plasticizer	Bouzenad *et al.* (2024a)
Sargassum filipendula	Brazil	Agar/alginate/collagen + GSE	Good food contact safety	Limited water resistance	Wang and Rhim (2015)
Commercial alginate	/	Alginate + PAW + Citric acid	Reduced WVP, improved film morphology	Requires specialized equipment	Sharmin *et al.* (2021b)
Commercial alginate	/	Alginate + Babassu mesocarp	Enhanced tensile strength	Requires hydrophobic plasticizers	Lopes *et al.* (2020)
Commercial alginate	/	Alginate-pectin + Cinnamic acid	Active packaging for meat	High cost of active agents	Tong *et al.* (2023)
Commercial alginate	/	Alginate + Stevia extract	Safe, edible coating	Short shelf life	Amariei *et al.* (2022)

and films for food packaging. Similar to protein-based films described by Gennadios (2002), alginate coatings can be modified through plasticizers and cross-linkers to improve their functional and mechanical behavior. These films can be produced through methods like casting and external gelation, with variations in additives such as glycerol, calcium chloride, or natural extracts to tailor their properties for specific applications. For instance, films with hydrolyzed collagen displayed uniform thickness and improved moisture resistance, making them suitable as coatings to enhance shelf life and reduce spoilage of food products (Marangoni Júnior *et al.*, 2021). Similarly, films incorporating guava leaf extracts demonstrated smooth and cohesive film formation, suitable for coatings that protect against environmental factors (Luo *et al.*, 2019). Alginate coatings enhanced with ascorbic acid and calcium chloride have also shown potential for improving mechanical strength and transparency, vital for visual appeal in food packaging (Amariei *et al.*, 2022). Coating applications for fruits, vegetables, and other perishable foods benefit from these enhanced barrier and mechanical properties. For example, films incorporating thymol and cinnamic acid were effective in maintaining the quality of fresh-cut apple slices and beef by reducing microbial growth and preserving color and moisture (Davis *et al.*, 2004; Wang *et al.*, 2023).

Alginate-based coatings with active ingredients such as natamycin have also shown potential in preventing fungal growth on perishable foods (Bierhalz *et al.*, 2012). Additionally, edible coatings derived from blends of alginate and agar, enriched with stevia, provide protective barriers that are both biodegradable and beneficial for food safety (del Olmo *et al.*, 2019). Additionally, edible coatings made from alginate and other biopolymers, enriched with natural extracts, provide protective, biodegradable barriers safe for food contact. The versatility and effectiveness of alginate-based films and coatings make them a sustainable alternative to conventional food packaging.

Alginate blends and composites with other materials

Blending alginate with biopolymers such as chitosan or starch, along with natural additives, enhances the functional properties of alginate films. These blends offer synergistic benefits, including improved mechanical strength, reduced moisture permeability, and bioactive functionalities. For instance, alginate films incorporating cotton seed protein hydrolysates demonstrated increased antioxidant activity and enhanced moisture barrier properties, making them suitable for fatty food applications (de Oliveira Filho *et al.*, 2019). The combination with babassu coconut mesocarp also demonstrated enhanced structural integrity and mechanical stability (Lopes *et al.*, 2020).

Additionally, agar and collagen blends enriched with silver nanoparticles or grapefruit seed extract employment have been shown to enhance the antimicrobial properties and moisture resistance of the films, making them ideal for active packaging applications (Wang and Rhim, 2015).

Incorporating nanocomposites, such as Au-TiO_2, into alginate films enhances their antimicrobial and photocatalytic properties, which are beneficial for packaging applications that require active functionalities to prevent microbial growth (Tang *et al.*, 2018). The use of hydrophobic plasticizers, such as tributyl citrate, also improves moisture resistance and mechanical properties, offering tailored solutions for different packaging needs (Paixão *et al.*, 2019). Moreover, the development of films incorporating tannic acid has provided additional antioxidative and antimicrobial benefits, expanding the versatility of alginate-based packaging (Li *et al.*, 2022). Overall, these alginate blends and composites offer innovative and sustainable packaging solutions that meet the growing demand for eco-friendly materials while providing a wide range of functional benefits.

Active packaging

Alginate films can be modified to include active agents that provide antimicrobial properties, making them effective for active packaging solutions. Comparable approaches using N,O-carboxymethyl chitosan have demonstrated similar bioactivity enhancements (Dixit *et al.*, 2022). For instance, alginate films incorporated with thymol, cinnamic acid, or microencapsulated carvacrol exhibited significant antimicrobial activities against common foodborne pathogens, making them suitable for packaging applications that require inhibition of microbial growth to extend shelf life (Davis *et al.*, 2004; Urtuvia *et al.*, 2017). Similarly, the incorporation of silver nanoparticles and grapefruit seed extract in agar/alginate/collagen films provided strong antimicrobial and moisture barrier properties, enhancing their effectiveness in food packaging (Wang and Rhim, 2015). Alginate films enriched with cinnamic acid have also been utilized effectively in active packaging for meat products, showing significant reductions in microbial growth (Tong *et al.*, 2023). Smart packaging applications, such as pH-responsive films incorporating beetroot extract, can indicate spoilage through visible color changes, enabling real-time monitoring of food freshness (Chen *et al.*, 2021). Similarly, natural pigments obtained via UAE, such as Berberis-derived anthocyanins (Vega *et al.*, 2025), can serve as freshness indicators in alginate films. These functionalities not only enhance food safety but also contribute to reducing food waste by providing clear indicators of product quality. Additionally, films with guava leaf extracts have demonstrated the potential for integrating natural antioxidant and antimicrobial properties, offering a dual function in active and intelligent packaging solutions (Luo *et al.*, 2019). Ultrasound-induced pigment production from microbial or plant sources may further support the development of alginate-based smart indicators (Kulkarni *et al.*, 2018). Overall, these modifications position alginate films as a promising material for next-generation food packaging solutions that address both consumer safety and environmental sustainability.

Case studies of alginate as food packaging

Several case studies highlight the effectiveness of alginate-based films in real-world food packaging scenarios. For instance, sodium alginate–pectin films with cinnamic acid were used to wrap fresh beef, which effectively reduced bacterial growth and preserved meat color quality over the storage period (Tong *et al.*, 2023). Similarly, thymol/sodium alginate films applied to fresh-cut apple slices maintained apple quality by reducing weight loss and preventing browning (Chen *et al.*, 2021). Other studies demonstrated the films' effectiveness in reducing moisture loss and microbial growth on perishable foods, confirming their potential for broader application in food packaging (Cheng *et al.*, 2019). Alginate films functionalized with tannic acid have also shown promise in providing antioxidative and antimicrobial effects suitable for packaging fresh produce (Li *et al.*, 2022). Additionally, the application of sodium alginate films with Au-TiO_2 nanocomposites in active packaging demonstrated significant antibacterial effects under light irradiation, supporting their use in scenarios where microbial control is critical (Tang *et al.*, 2018). These case studies reinforce the versatility and practicality of alginate-based films as sustainable and effective food packaging materials.

Sustainability and Environmental Impact

Alginate-based films offer a more sustainable alternative to traditional plastics due to their biodegradability and use of renewable resources. This perspective aligns with Davis and Song, (2006), who emphasized the potential of crop-derived biodegradable packaging to alleviate environmental stress caused by conventional plastics. Several studies have highlighted these environmental benefits, although a comprehensive life cycle analysis is often not provided (Mazumder *et al.*, 2016; Trica *et al.*, 2019). For example, films enriched with babassu coconut mesocarp or hydrolyzed collagen showcase approaches that valorize natural byproducts, contributing to a circular economy (Mohammed *et al.*, 2018; Yudiati *et al.*, 2018). Compared to petrochemical plastics, these alginate films not only reduce plastic waste but also offer the possibility of incorporating active functions, such as antimicrobial and antioxidant properties provided by natural extracts such as thymol and cinnamic acid (Prüsse *et al.*, 2008; Urtuvia *et al.*, 2017). Alginate films with sodium alginate–castor oil blends also demonstrate biodegradability and improved barrier properties, highlighting their potential to replace conventional plastics in food packaging (Aziz *et al.*, 2018). However, despite these environmental advantages, alginate films still need to overcome certain limitations to fully compete with traditional plastics in terms of performance. For instance, films enriched with plasticizers such as citric acid and plasma-activated water show improved mechanical and moisture barrier properties, but further optimizations are needed to meet the standards of synthetic packaging materials (Sharmin *et al.*, 2021b). Films incorporating pectin and natamycin also highlight the potential for enhanced antimicrobial activities, offering a dual benefit of extending shelf life while maintaining sustainability (Bierhalz *et al.*, 2012). While they provide significant environmental benefits and multifunctional properties, continued research and development are required to optimize their performance to fully match or exceed that of conventional synthetic packaging materials. By overcoming these limitations, alginate films could play a crucial role in the future of sustainable food packaging, reducing reliance on nonrenewable resources and minimizing environmental impact.

Challenges and Future Prospects

Current limitations

Alginate-based films encounter technical and economic challenges, particularly when it comes to large-scale production. The need for precise cross-linking conditions and the incorporation of specific additives, like microencapsulated carvacrol or Au-TiO_2 nanocomposites, increase the complexity and costs of manufacturing, posing obstacles to widespread commercial adoption (Bojorges *et al.*, 2022; Ching *et al.*, 2017). Additionally, while some films enhanced with nanomaterials or natural fibers show improved performance, they often remain inferior to traditional plastics in terms of mechanical robustness and water vapor permeability (Bouzenad *et al.*, 2024a; Valentine *et al.*, 2020). Films with sodium alginate and copper oxide nanoparticles have shown promising enhancements in barrier properties, though uniform dispersion and cost management remain critical challenges (Saravanakumar *et al.*, 2020). To overcome these limitations, ongoing research is exploring blends of biopolymers and the addition of nanofillers to enhance the functional properties of the films. For example, the integration of cellulose nanocrystals and copper oxide nanoparticles has shown promising improvements in antimicrobial and barrier properties, although challenges remain in terms of uniform dispersion and cost management (Saravanakumar *et al.*, 2020). Additionally, the development of smart films capable of responding to environmental stimuli to indicate food freshness could represent a significant advancement for alginate-based packaging, broadening their utility in the food sector (Chen *et al.*, 2021). Further, films that incorporate tannic acid and other natural extracts continue to offer avenues for enhancing the bioactivity and sustainability of packaging materials (Li *et al.*, 2022). However, despite these advantages, challenges remain in terms of optimizing mechanical properties, scalability, cost-effectiveness, and achieving the performance levels required for widespread commercial use. Future innovations, such as blending with other biopolymers, incorporating nanomaterials, and developing smart packaging solutions, offer pathways to overcome these limitations. Continued research and development efforts are crucial to unlocking the full potential of alginate-based films, paving the way for more sustainable and multifunctional packaging solutions that align with environmental goals and the evolving needs of the food packaging industry.

Conclusions

This review highlights the potential of alginate as a sustainable material for food packaging, emphasizing its biodegradability, renewability, and ability to be functionally modified. It explores various aspects of alginate, including its natural sources, extraction techniques (mechanical, chemical, enzymatic, ultrasound-assisted, and microwave-assisted), synthesis, and industrial production. Optimizing these processes is essential for enhancing alginate yield, purity, and performance, thereby broadening its applications in food packaging.

Alginate-based films and coatings exhibit excellent barrier properties against moisture, oxygen, and light, along with notable mechanical strength and flexibility. Their ability to incorporate bioactive agents, such as antimicrobial and antioxidant compounds, further enhances their functionality, making them a viable alternative to synthetic plastics. Additionally, advances in blending alginate with other biopolymers, integrating nanomaterials, and applying cross-linking techniques have significantly improved its mechanical properties, expanding its potential applications in the packaging industry.

However, despite its advantages, challenges remain regarding large-scale production, cost-effectiveness, and mechanical durability compared to conventional plastics. Addressing these limitations requires continued research into optimizing formulations, refining extraction and processing methods, and incorporating advanced reinforcement strategies such as nanotechnology and smart packaging solutions. Collaboration among material scientists, engineers, and industry stakeholders will be crucial in overcoming these barriers and accelerating the commercialization of alginate-based packaging.

By leveraging these advancements, alginate has the potential to play a key role in the transition toward sustainable packaging solutions. Its adoption in industrial applications can contribute to a circular economy, reducing plastic waste while meeting consumer and regulatory demands for environmental friendly, high-performance materials.

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Authors Contribution

All authors contributed equally to this article.

Conflicts of Interest

The authors declare no conflict of interest.

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