

# Use and bioavailability of polysaccharides from algal source as polymeric biomaterials in the food industry

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*Uso y biodisponibilidad de polisacáridos de fuente algal como biomateriales poliméricos en la industria alimentaria.*

*Ús i biodisponibilitat dels polisacàrids de font d'algals com a biomaterials polimèrics a la indústria alimentària.*

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## ABSTRACT

The use of natural polymers has surged due to concerns about environmental pollution from plastics and emerging pollutants from fossil fuels. Within this framework, polysaccharides derived from macroalgae and microalgae are recognized as abundant natural resources suitable for diverse applications in biology, biomedicine, and food industries. These polysaccharides are used to create various nanomaterials that serve as effective carriers in the food sector. Incorporating polysaccharide-based nanomaterials as functional food ingredients can enhance texture properties and reduce caloric density. Furthermore, these nanostructures show promise in developing food packaging with antioxidant and antimicrobial properties. Importantly, polysaccharide-based nanomaterials are biocompatible and biodegradable. This review article thus explores the utilization of algal polysaccharides for manufacturing nanomaterials and their potential application across the food field. Furthermore, the article examines the role of algae as a source of polysaccharides, nanomaterials derived from these biopolymers, recent advances in research and potential applications in the food industry.

**Keywords:** Polymers, nanomaterials, algae, biocompatible, biodegradable.

## RESUM

L'ús de polímers naturals ha augmentat a causa de la preocupació sobre la contaminació ambiental dels plàstics i els contaminants emergents dels combustibles fòssils. En aquest marc, els polisacàrids derivats de macroalgues i microalgues són reconeguts com a recursos naturals abundants aptes per a diverses aplicacions en biologia, biomedicina i indústries alimentàries. Aquests polisacàrids s'utilitzen per crear diversos nanomaterials que serveixen com a portadors efectius en el sector alimentari. La incorporació de nanomaterials basats en polisacàrids com a ingredients alimentaris funcionals pot millorar les propietats de la textura i reduir la densitat calòrica. A més, aquestes nanoestructures són prometedores en el desenvolupament d'envasos d'aliments amb propietats antioxidants i antimicrobianes. És important destacar que els nanomaterials basats en polisacàrids són biocompatibles i biodegradables. Així, aquest article de revisió explora la utilització dels polisacàrids d'algues per a la fabricació de nanomaterials i la seva aplicació potencial a l'àmbit alimentari. A més, l'article examina el paper de les algues com a font de polisacàrids, nanomaterials derivats d'aquests biopolímers, avenços recents en recerca i possibles aplicacions a la indústria alimentària.

**Paraules clau:** Polímers, nanomaterials, algues, biocompatibles, biodegradables.



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## RESUMEN

El uso de polímeros naturales ha aumentado debido a las preocupaciones sobre la contaminación ambiental causada por los plásticos y los contaminantes emergentes de los combustibles fósiles. En este marco, los polisacáridos derivados de macroalgas y microalgas son reconocidos como recursos naturales abundantes aptos para diversas aplicaciones en biología, biomedicina e industrias alimentarias. Estos polisacáridos se utilizan para crear diversos nanomateriales que sirven como portadores eficaces en el sector alimentario. La incorporación de nanomateriales a base de polisacáridos como ingredientes alimentarios funcionales puede mejorar las propiedades de textura y reducir la densidad calórica. Además, estas nanoestructuras son prometedoras en el desarrollo de envases de alimentos con propiedades antioxidantes y antimicrobianas. Es importante destacar que los nanomateriales a base de polisacáridos son biocompatibles y biodegradables. Por lo tanto, este artículo de revisión explora la utilización de polisacáridos de algas para la fabricación de nanomateriales y su posible aplicación en el campo alimentario. Además, el artículo examina el papel de las algas como fuente de polisacáridos, nanomateriales derivados de estos biopolímeros, avances recientes en investigación y posibles aplicaciones en la industria alimentaria.

**Palabra clave:** Polímeros, nanomateriales, algas, biocompatibles, biodegradables.

## INTRODUCTION

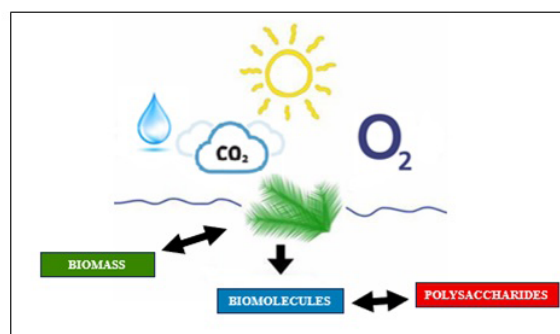
The use of green polymers has seen a rise due to concerns over marine plastic pollution and the discovery of emerging pollutants. Polysaccharides are macromolecules composed of monosaccharide units linked by glycosidic bonds. These molecules exhibit diverse chemical natures and characteristics due to their varied sources. They are abundant in nature and possess biodegradable and biocompatible properties. Moreover, polysaccharides are renewable and non-toxic. Their hydrophilicity, mechanical stability, and adjustability are additional advantages. Polysaccharides can be extracted from renewable sources such as algae, vegetables, microorganisms, and animals [1–6].

Algae and microalgae, in particular, are sustainable alternatives for biopolymer production under the biorefinery model. They feature rapid growth rates, adaptability to various conditions, and utilization of carbon dioxide (CO<sub>2</sub>), and they do not compete with food resources (Figure 1).

Quality control measures and advanced cultivation techniques are essential for obtaining high-quality polysaccharides. The extraction process significantly influences the composition and molecular weight of biopolymers, emphasizing the importance of selecting the optimal extraction method <sup>7,8</sup>.

Historically, algal polysaccharides such as agar, alginates, and carrageenans have been industrially produced

for over a century. These polymers hold potential for various applications in food and the production of high-value products extensively researched in biomedicine. Algae and microalgae serve as promising raw materials for biomaterials and nanomaterials. Polysaccharides derived from these sources can be transformed into nanoparticles, finding applications across diverse fields including food, feed, cosmetics, biomedicine, and modern medicine. Examples include their use as wound dressings and in gene and drug delivery [7,9–12].



**Figure 1.** Diagram of the photosynthesis process of algae and microalgae to obtain biomass (Own Authorship).

However, the production of nanomaterials using polysaccharides involves complex designs and high preparation costs <sup>13</sup>, posing challenges such as low yield and high cost that hinder their market penetration <sup>6</sup>. Extracting valuable components from algal polysaccharides remains economically challenging due to their compacted cellular structure, which increases processing expenses <sup>14</sup>. Moreover, some polysaccharides exhibit low solubility in common solvents, limiting their chemical modification potential <sup>15</sup>. Therefore, there is a growing need for cost-effective advanced synthesis processes and the adoption of green and recyclable solvents to promote the commercial synthesis of polysaccharide-based nanoparticles in industries. Efforts should focus on developing sustainable and cost-effective approaches, such as derivatizing seaweed polysaccharides with other macromolecules, and investigating their in vivo actions for nutraceutical delivery <sup>13,15</sup>.

This review article explores the use of algal polysaccharides in manufacturing nanomaterials and their potential applications in the food and biomedical sectors. It covers general aspects of algae as a source of polysaccharides, the types of nanomaterials derived from these polymers, recent research findings, and the potential industrial applications of algal polysaccharides.

### Biomass Algae as sources of Polysaccharides

Polysaccharides in macroalgae are categorized into two types: structural polysaccharides found on the cell surface and storage polysaccharides located intracellularly. The former include alginates, carrageenans, cellulose, sulfated polysaccharides, fucoidans, and ulvans. Among the storage polysaccharides, laminarin and

starch are the most well-known examples<sup>16</sup>. Over the years there are tons of agro-waste which are generated from a wide variety of industries. These residues are rich in polysaccharides and can be used for a number of purposes. As the polysaccharide market is growing with each passing year, the need for a sustainable source is under continuous quest. Much of the agricultural waste (residual biomass) is a significant environmental concern that needs urgent consideration.

Sulfated polysaccharides like carrageenans and agar are characteristic of red algae<sup>17</sup>. Brown algae typically contain fucoidans, alginates, and laminarin, while ulvans are predominantly found in green algae<sup>18</sup>. Cellulose and hemicelluloses are prevalent in the extracellular coverings of Chlorophyta and Charophyta (green algae), Rhodophyta (red algae), and within the *Ochrophyta* phylum and *Phaeophyceae* class (brown algae). Some species of *Xanthophyceae* (yellow-green algae), the *Chrysophyceae* class (golden algae), and *Dinophyta* (thecate dinoflagellates) utilize cellulose as a structural polysaccharide for their cell walls<sup>19</sup>.

However, through aquaculture, various cultivation techniques can be explored to enhance algae polysaccharide yields and promote environmental sustainability. Tanoeiro et al.,<sup>20</sup> investigated cultivation methods for *Chondrus crispus* and found that the free-floating balloon method, with periodic water changes three times a week, yielded the highest carrageenan content. Despite these advancements, seaweed cultivation still lags behind harvesting, typically yielding approximately 50% carrageenan content. Nonetheless, aquaculture offers a promising approach to ensure sufficient carrageenan supply without depleting natural populations, thereby representing a more sustainable alternative as *C. crispus* becomes scarcer in its natural habitat.

Similar to macroalgae, microalgae also possess the ability to produce polysaccharides. These polysaccharides can either form part of the cell wall (such as starch)

or be excreted outside the cells as exopolysaccharides (EPS) in response to environmental stresses. Therefore, cultivation strategies can be employed to stimulate the production of these cultures (see Table 1)<sup>21</sup>.

Both macroalgae and microalgae benefit from biorefinery techniques. In the case of macroalgae, multiple types of polysaccharides can be obtained from the same species through sequential extractions. Birgersson et al.,<sup>22</sup> utilized an integrated process to recover alginates, fucoidans, laminarin, and cellulose from *Saccharina latissima* and *Alaria esculenta*, yielding 23.4% and 26.3% polysaccharides from dry biomass, respectively. Mild chemical methods were employed to preserve the molecular weights of polysaccharides, particularly alginates. In contrast, polysaccharide production from microalgae follows a different biorefinery approach. Here, the focus is on extracting high-value components including exopolysaccharides (EPS), which are excreted into the culture medium. The remaining products are separated from the biomass, including fatty acids, phycocyanin, other pigments, biofuels, food products, biofertilizers, and energy<sup>8,22</sup>. Microalgae cultivation can utilize saline, brackish water<sup>23,24</sup>, and even wastewater<sup>25</sup> as culture media.

Gaseous effluents can also serve as nutrient sources for microorganism cultivation<sup>26</sup>. Strategies such as supplementing cultures with phytohormones<sup>27</sup> can further enhance biomass productivity and reduce production costs. These approaches make microalgae biorefinery highly productive, sustainable, and economically viable for industrial applications, potentially increasing the market share of microalgal polysaccharides.

### Use of polysaccharides from algal sources in the food field

Algal and microalgal polysaccharides have garnered attention in various food applications due to their functional properties and potential health benefits

**Table 1.** Extraction Method polysaccharides from algae.

Microalgae	Extraction Method	Polysaccharides Type	Polysaccharides Yield (%w)	Reference
<i>Saccharina latissima</i>	Typical extraction (acidification—HCl, alkaline extraction—Na <sub>2</sub> CO <sub>3</sub> ), solid/liquid separation, precipitation, and drying)	Cellulose	26	28
<i>Arthrospira platensis</i> SAG21.99	Microwave-assisted hydrothermal(liquid phase/ EtOH,1:1.5, choline chloride 1%, 120°C)	Ulvans	41	29
<i>Spirulina platensis</i>	Commercial microalgal powder was extracted with ultrapure water and ultrasonic treatment (45kHz,300w) at 60 °C for 1h.	Polysaccharide of <i>Spirulina platensis</i>	27.3	30
<i>Chlorella vulgaris</i>	BG11medium, light intensity 65 mol photons 2s 1and temperature28 C	Heteropolysaccharides	32.7	31
<i>Chlorella fusca</i> LEB111	Outdoor cultures; static magnetic fields application for 1 hour.	Starch	10.9	21,31

<sup>9,10</sup>. In the food industry, these polysaccharides are employed as natural additives for their abilities in gelling, stabilizing, and emulsifying, and are also used in packaging (such as edible coatings or films for active and intelligent packaging) <sup>32</sup>.

Microalgae-based polysaccharides are categorized into structural polysaccharides (like cellulose in the cell wall), storage polysaccharides (including starch and glycogen stored in the chloroplast), and extracellular polysaccharides (secreted for intercellular communication). These polysaccharides exhibit anti-inflammatory and immunomodulatory properties, contributing to their use in nutraceutical production <sup>33</sup>. Both algae and microalgae polysaccharides possess biocompatible properties, low toxicity, and the ability to form gels in response to metal ions or pH changes, making them versatile for diverse applications <sup>9,33</sup>. Moreover, certain marine polysaccharides such as chitosan, sodium alginate, and agar have demonstrated antibacterial and antioxidant properties, along with biocompatibility, which are beneficial for food preservation and improving the physicochemical attributes of food products <sup>34</sup>.

The dried biomass of algae such as *Spirulina* or *Chlorella* has found application in traditional food products such as bread, soups, and cookies <sup>35,36</sup>. However, sensory evaluations suggest that low concentrations of algae (around 0.5%) are more acceptable to potential consumers due to the distinct sensory characteristics of microalgae <sup>35,36</sup>. Technologies like enzyme-assisted extraction or ultrasound are utilized to recover polysaccharides from microalgae for incorporation into functional foods, nutraceuticals, or supplements <sup>37</sup>. An example of polysaccharide application in food is *Spirulina*, which contains polysaccharides widely used as food additives or colorants in ice creams, chewing gums, candies, dairy products, soft drinks, and jellies <sup>38</sup>.

Sulfated polysaccharides are prominent in commercial food applications due to their stabilizing, gelling, emulsifying, and viscosity-increasing properties. These compounds play a crucial role in the food industry by enhancing the structure of various food products, including jams, jellies, ice cream, and dairy items, where they are commonly used as additives <sup>39</sup>. Additionally, sulfated polysaccharides are utilized to inhibit the growth of foodborne pathogens such as *Escherichia coli*, *Staphylococcus aureus*, and *Salmonella enterica* <sup>40</sup>. Agar, another widely used polysaccharide, finds extensive application in food processing, including pastry fillings, jams, confections, beverages, spreads, garnishes, puddings, desserts, ice cream, as well as in meat and poultry products. It is particularly valued for its role in preparing jellies, where hot agar extract is mixed with food colors and flavors, then molded and cooled <sup>41</sup>. Carrageenan is also widely employed for commercial purposes in the food industry.

Sulfated polysaccharides, renowned for their excellent functional properties as thickening agents, stabilizers, and texture modifiers, significantly enhance the appearance and quality of food in various commercial applications. They are extensively utilized in the dairy, baking, and food processing industries for products

like puddings, milkshakes, instant soups, sauces, jellies, and pastes <sup>42</sup>.

In the biomedical field, microalgal polysaccharides have been investigated for diverse applications such as drug delivery systems, tissue engineering, wound dressings, cancer therapy, bone regeneration, and as antibacterial and antiviral agents <sup>10,42</sup>. The biological activities of these polysaccharides and exopolysaccharides can be observed through direct extracts or purified compounds. They have demonstrated various beneficial effects including anti-tumor properties <sup>43</sup>, antioxidant effects <sup>44</sup>, antiviral activity <sup>45</sup>, anti-inflammatory properties <sup>33,44,45</sup>, and antimicrobial activity <sup>46</sup>. Sulfated polysaccharides derived from marine sources are particularly noted for their immunological, antiviral, probiotic, and prebiotic properties. Their diverse structures have shown promising responses against the COVID-19 virus (SARS-CoV-2), enhancing the host's antiviral response by interfering with virus attachment, adsorption, replication, and translation processes <sup>47</sup>. Moreover, these compounds can modulate the immune response against SARS-CoV-2 through various mechanisms. For instance, polysaccharides like carrageenans can act as effective adjuvants to improve the efficacy of peptide-based vaccines through immune enhancement <sup>48</sup>.

Algal polysaccharides are notable for their antioxidant activity, which holds potential for applications in both food and biomedical fields <sup>49</sup>. For example, polysaccharides extracted from *Chlorella pyrenoidosa* were precipitated using various concentrations of ethanol, and their antioxidant capabilities were assessed by measuring hydroxyl radical scavenging, DPPH radical scavenging, and superoxide anion scavenging activities. The findings indicated that these polysaccharides effectively scavenged free radicals in vitro <sup>44,45</sup>.

### Focus on polysaccharides in the area of nanomaterials

With the rapid advancement of nanobiotechnology, nanomaterials have made significant inroads into the food and pharmaceutical sectors, providing clinical and medical benefits to consumers <sup>50</sup>. Polysaccharide-based nanosystems, in particular, have shown promise in reducing drug toxicity and minimizing side effects <sup>51</sup>.

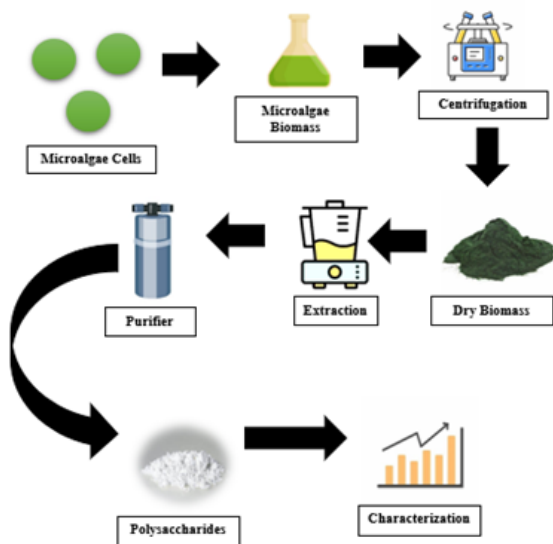
Nanomaterials derived from algae and microalgae have garnered attention due to their favorable physicochemical properties, stability, and cost-effectiveness. These materials also exhibit characteristics such as hydrophilicity, high biodegradability, and biocompatibility <sup>52</sup>. Algal compounds, including polysaccharides, are capable of forming nanomaterials due to their precise and controllable structures (see Table 2).

According to Qiu et al., <sup>57</sup>, polysaccharide-based nanocarriers encompass various forms including nanoliposomes, nanoparticles, nano micelles, nano-emulsions, and nanohydrogels. Notably, nanoparticles, nanofibers, and nanogels are particularly prominent <sup>58,59</sup>. In Figure 2, a general process for obtaining algal

**Table 2.** Production of nanomaterials based on algal polysaccharides.

Algae	Polysaccharides	Manufacturing	Outcomes	Reference
<i>Sargassum angustifolium</i>	Fucoidan	Ultrasonic treatment was used to prepare nanoemulsions for fucoxanthin encapsulation	Controlled release under gastrointestinal conditions; encapsulation efficiency of 79%.	53
<i>Chlorella vulgaris</i>	Carbohydrates containing polysaccharide	Secreted carbohydrates by microalgal cells were used for reducing and capping silver nanoparticles.	Anticancer and antimicrobial applications.	54
<i>Spirulina maxima</i>	Pectin	Pectin was extracted from microalga and then modified using high temperature and pressure for a specific duration. Subsequently, pectin nanoparticles were created through sonication of the modified pectin.	Potential to modulate gut microbial community, enhance the expression of immune-related genes, and improve gut morphology	55
<i>Spirulina platensis</i>	Spirulina polysaccharides	Selenium nanoparticles with Spirulina polysaccharides have been developed with a solution-phase method. Microalgal polysaccharides were extracted with hot water.	Enhanced cellular uptake and anticancer efficacy, are potential candidates for further evaluation as a chemopreventive and chemotherapeutic agent against human cancers.	56

biomass, the polysaccharide extraction process, as well as their respective characterization can be observed.



**Figure 2.** Process of obtaining algal biomass (Own Authorship).

The abundance and biocompatibility of polysaccharides highlight their potential as carriers for bioactive compounds. Techniques such as ionic gelation, emulsion, and polyelectrolyte complexation are commonly employed to convert polysaccharides into nanoparticles. Ionic gelation and polyelectrolyte complexation involve the addition of cationic molecules to anionic polysaccharides, facilitating the formation of stable polymeric nanoparticles with controlled shape, size, and charge <sup>60</sup>. Polysaccharides derived from algae can thus be used to produce such nanoparticles, depicting the main structures of polysaccharides extracted from commercially relevant algal biomass. These nanomaterials can be based on algal polysaccharides (e.g. alginate, carrageenan, agars, and fucoidan).

On the other hand, nanofibers are elongated thin structures made from synthetic polymers, natural polymers, or biopolymers. These nanomaterials possess diverse mechanical, electrical, and thermal properties, making them applicable across pharmaceutical, cosmetic, textile, and food industries. Their high porosity allows for the controlled release of various agents with efficient transport capacities. Nanofibers can be fabricated through methods such as phase separation, drawing, and electrospinning. Electrospinning offers advantages in scalability, reproducibility, and the use of mild conditions for incorporating bioactive compounds and polymers into fibers <sup>61,62</sup>. Polysaccharide-based nanofibers leverage their high porosity, small pore size, and large surface area for applications in drug delivery, tissue engineering, bone regeneration, and wound dressing. These nanofibers have demonstrated promising results in safely administering drugs <sup>63</sup>.

Nanogels, on the other hand, are nanometer-sized hydrogels formed by the crosslinking of polymeric chains, offering high mechanical stability, efficient drug-loading capacity, and responsiveness to environmental stimuli for controlled release <sup>64,65</sup>. Polysaccharides, as natural hydrogel-forming polymers, are commonly isolated from algae and utilized to create nanogels <sup>66</sup>. Therefore, ongoing research and development focus on maximizing and enhancing nano-delivery systems based on polysaccharides sourced from algae, highlighting their potential in various applications.

Increasing consumer awareness about health-promoting foods has spurred the food industry to develop products enriched with bioactive compounds <sup>67</sup>. Nanotechnology offers significant contributions by enabling the nanoencapsulation of bioactive compounds, thereby safeguarding them from degradation during processing and storage. This approach enhances stability, bioavailability, and preserves their bioactivity <sup>68,69</sup>. Polysaccharides play a crucial role as encapsulating agents in the food industry, preventing the loss of volatile compounds and improving the dispersion of poorly soluble compounds within the food matrix <sup>69</sup>.

Polysaccharides derived from algae possess desirable characteristics for encapsulation, including bioavailability, biocompatibility, bioactivity, and non-toxicity<sup>70</sup>. For example, Fucoidan specifically, has been investigated as part of polymeric matrices for nanoencapsulation to address challenges such as low solubility in water and sensitivity to temperature and pH variations<sup>71</sup>. Studies have demonstrated that using fucoidans in the encapsulation of bioactive compounds like curcumin, quercetin, and resveratrol improves their stability and enables controlled release during simulated digestion *in vitro* [72-74]. This polysaccharide shows promise in effectively preserving bioactive ingredients incorporated into functional foods.

Roy et al.,<sup>75</sup> explored the compound  $\kappa$ -carrageenan as a stabilizer for quercetin-loaded zein colloidal particles. This polysaccharide was used to coat the hydrophobic zein, allowing dispersion in water, greatly improving thermostability, which facilitated controlled release and increased antioxidant activity. Consequently, this system serves as an effective medium for bioactive compounds possessing hydrophobic characteristics. Compared to what was previously described, Gallón et al.,<sup>76</sup> investigated exopolysaccharides produced by microalgae *Chlorella pyrenoidosa* and *Botryococcus braunii* as stabilizers in the synthesis of silver nanoparticles. These exopolysaccharides facilitated the production of nanoparticles with controlled size and stable dispersion. The resulting nanoparticles exhibited antibacterial activity against both *Staphylococcus aureus* and *Escherichia coli*, including methicillin-resistant *S. aureus*, suggesting potential applications as antimicrobials in food packaging. Oliyaei et al.,<sup>53</sup> studied the stabilization of nanoemulsions using natural polysaccharides as emulsifiers to encapsulate fucoxanthin.

Fucoidans demonstrated higher encapsulation efficiency (79%) compared to gum Arabic. Both polysaccharides exhibited controlled release of fucoxanthin during simulated digestion *in vitro*.

Richa and Choudhury<sup>77</sup> investigated fucoidans and  $\kappa$ -carrageenan as emulsifiers in nanoemulsion formulations for curcumin encapsulation, finding comparable properties to Tween 20. They observed that fucoidans and levan enhanced the antioxidant activity of the nanoemulsions. Polysaccharides are also being explored for food packaging due to their inherent protective function, gel-forming capacity, and barriers against oxygen and carbon dioxide. However, their hydrophilic nature leads to poor water vapor barrier properties and mechanical stability<sup>78</sup>. To address these limitations, nanocomposites derived from polymer blends incorporating nanoparticles offer a promising solution to enhance the properties of films made from algal polysaccharides<sup>79</sup>. Numerous studies have investigated the development of films using nanoformulations containing algal polysaccharides and nanoparticles for potential applications in food packaging<sup>80</sup>.

The polysaccharide  $\kappa$ -carrageenan has been utilized in the development of nanocomposite films along with konjac glucomannan and titanium dioxide nanoparticles. This nanocomposite film demonstrated several beneficial properties including thermal stability, UV

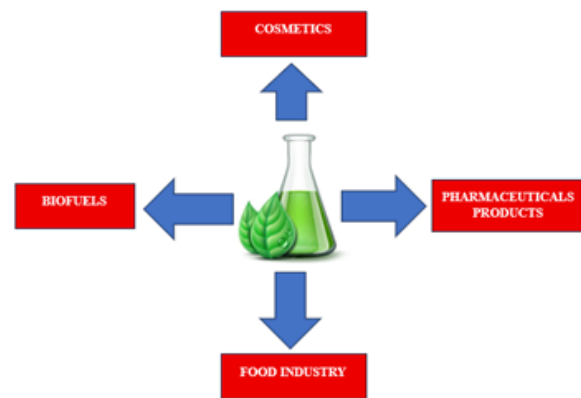
light barrier properties, mechanical strength, low water vapor permeability, hydrophobicity, and antifungal capabilities. When applied as packaging for strawberries, this film effectively inhibited the growth of *Penicillium viridicatum*, reduced weight loss, and minimized titratable acidity compared to strawberries packaged in traditional plastic packaging or left unpackaged<sup>81</sup>.

Similarly, nanocomposite films based on  $\kappa$ -carrageenan and silver nanoparticles have been developed with properties such as UV light barrier, mechanical durability, thermal stability, and antimicrobial activity against foodborne pathogens like *Escherichia coli* and *Listeria monocytogenes*<sup>75,80,81</sup>. Another study focused on agar-based nanocomposite films reinforced with zinc minerals, which exhibited enhanced barrier properties against gases and moisture, improved mechanical strength, and antimicrobial effects against bacteria such as *Staphylococcus aureus* and *Candida albicans*<sup>81</sup>.

These studies underscore the potential of nanocomposite films based on algal polysaccharides for food packaging applications. They offer robust solutions to preserve food quality by preventing contamination and maintaining freshness during storage, thereby addressing key challenges in food safety and shelf-life extension.

#### Industrial Potential of Algal Polysaccharides

The potential applications of polysaccharides produced by algae in several industrial sectors and the rising demand for sustainable products can boost the market for these polysaccharides (Figure 3).



**Figure 3.** Applications of algal biomass in different sectors (Own Authorship).

The global seaweed polysaccharides market has exhibited steady growth in recent years. Projections indicate that sales of these products will increase from USD 1 million in 2023 to approximately USD 3 million in 2033<sup>82,83</sup>.

In this context, several companies that produce and commercialize polysaccharides from macroalgae have been identified. One such product is FoodGel™ Carrageenan, the polysaccharide  $\kappa$ -carrageenan extracted from the seaweed *Eucheuma cottonii* and produced by the Food Chem company<sup>84</sup>. This product is of food-grade quality and is commonly used as an emulsifier and stabilizer in the food industry. Other companies producing this polysaccharide for application in food products are Cargill<sup>85</sup>, CP Kelco<sup>86</sup>, and Gelymar<sup>87</sup>.

Maritech<sup>®</sup> is the fucoidan polysaccharide extracted and purified from seaweed. It is produced by Marinova Pty Ltd. for application in functional foods and beverages, dermatological formulations, and animal health products<sup>88</sup>. Gely<sup>™</sup>Alg is a line of sodium alginate products obtained from brown algae by the company Gelymar with wide application in the food and pharmaceutical industries<sup>89</sup>.

However, the industrial production of microalgal polysaccharides is still limited. The main market is the production of microalgal EPS for application in the cosmetics industry due to its antioxidant, anti-inflammatory, and antimicrobial properties<sup>90</sup>. Companies predominantly obtain this polysaccharide from the microalgae *Porphyridium cruentum*<sup>90</sup>.

Regarding the nanotechnological application of algal polysaccharides, although research has shown promising results in several areas, the commercialization of these products may require further advances in research. Bioavailability, toxicity, and production costs should be further explored, as well as regulatory issues<sup>91</sup>.

### Some future perspectives on the use and availability of polysaccharides extracted from microalgae

The challenges associated with producing polysaccharides through microalgae cultivation are critical to understanding the entire production process. Different approaches are applied in microalgae cultivation to obtain polysaccharides; however, there are common bottlenecks that hinder a cost-effective production process. These problems include:

Limited data on industrial-scale polysaccharide production from microalgae, along with a lack of guidance on extrapolation of parameters from laboratory-scale production to commercial production.

High operating costs in microalgae production related to nutrient availability and replenishment: CO<sub>2</sub> addition, electrical energy consumption, biomass recovery and trained personnel.

Feasibility of competitiveness of small-scale microalgae production systems against traditional products.

Difficulty in controlling microbial contamination in large-scale microalgae growth systems. High inorganic nutrient requirements and intensive energy consumption for microalgae cultivation and biomass drying.

Limited information on the relationship between microalgae species and polysaccharides of interest.

Low biomass productivity of microalgae compared to common microbial fermentation.

## CONCLUSIONS

Algae and microalgae are sustainable resources for producing biocompatible and renewable polysaccharides capable of synthesizing nanomaterials for applications in food and biomedical fields. Nanotechnology combined with polysaccharides of algal origin can prevent the loss of volatile compounds and improve the dispersion of low-solubility compounds in the food matrixes. Moreover, these nanomaterials are promising approaches for

developing packaging systems to preserve food quality. Packaging produced with added nanomaterials based on algal polysaccharides can improve barrier properties against UV light, mechanical properties, and permeability to water vapor.

Polysaccharide-based nanostructures also have attracted much attention in biomedical carriers due to their excellent encapsulation capacity. Polysaccharides derived from algae and microalgae demonstrate immunomodulatory, anti-inflammatory, antitumor, and antiviral properties for developing nanotechnological materials for biomedical applications. Algal polysaccharide nanomaterials can improve digestibility and nutrient availability, and they demonstrate potential for cancer chemoprevention and tissue engineering. In addition, using polysaccharides as a coating contributes to thermostability, a controlled release of bioactive compounds, and antioxidant and antimicrobial activities, which are promising characteristics for biomedical and food areas. Therefore, in addition to minimizing environmental contamination through CO<sub>2</sub> fixation, the contribution of microalgae to the production of polysaccharides extends to the manufacture of nanomaterials for various applications in the food and biomedical industry context.

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