 2024 Jun 12;16(12):1662. doi: 10.3390/polym16121662 Seaweed, a diverse and abundant marine resource, holds promise as a renewable feedstock for bioplastics due to its polysaccharide-rich composition. This review explores different methods for extracting and processing seaweed polysaccharides, focusing on the production of alginate plastic materials. Seaweed emerges as a promising solution, due to its abundance, minimal environmental impact, and diverse industrial applications, such as feed and food, plant and soil nutrition, nutraceutical hydrocolloids, personal care, and bioplastics. Various manufacturing techniques, such as solvent casting, injection moulding, and extrusion, are discussed for producing seaweed-based bioplastics. Alginate, obtained mainly from brown seaweed, is particularly known for its gel-forming properties and presents versatile applications in many sectors (food, pharmaceutical, agriculture). This review further examines the current state of the bioplastics market, highlighting the growing demand for sustainable alternatives to conventional plastics. The integration of seaweed-derived bioplastics into mainstream markets presents opportunities for reducing plastic pollution and promoting sustainability in material production. Keywords: alginate, hydrogel, bioplastic, marine resources, biopolymer, processing, seaweed

The term algae refers to a large phylogenetic unit that includes cyanobacteria, microalgae and macroalgae, and seaweed [1]. Seaweeds are macroscopic multicellular photosynthetic marine organisms [2,3] that usually grow in intertidal zones commonly between 30 and 40 m from the tidal channel but can reach depths of up to 180 m, mainly on solid substrates such as rocks, shells, and other materials. They can also be found in shallow coastal waters or estuaries [4]. Seaweeds have been employed since ancient times mainly in Asian countries [5,6], but nowadays, due to their availability and large diversity, seaweeds are considered globally as a novel source of bioactive components, such as peptides, amino acids, proteins, and polysaccharides. Thus, seaweeds have been used in a wide range of applications [7], such as human nutrition (43.77%) [8], animal feed (3.86%) [9], bioplastic production (5.34%) [10], and nutraceuticals (1.93%) [11]. As most of the species have no applications for human consumption, and can even act as invasive species when landing in different environments [12], they can be used as raw materials for the development of biodegradable materials [13], in line with the aim of a circular economy [14]. There are about 10,000 species of macroalgae estimated, classified into three main groups based on their pigmentation (Figure 1), i.e., green (Chlorophyceae), brown (Phaeophyceae), and red (Rhodophyceae) [15,16]. The composition of seaweeds varies depending on several factors such as the group and species to which they belong, the environmental conditions (e.g., temperature), the season, or the harvest location [17]. The approximate composition of different algae is presented in Table 1. 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 [18,19]. 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) [10,20,21]. Their chemical structure can be observed in Figure 2. 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 [22]. 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 [23]. 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 [24]. Agar is also extracted mainly from red algae and consists of a mixture of polysaccharides composed of agaropectin and agarose [25]. The most widespread use of alginate, carrageenan, and agar extracted from seaweed is as a gelling and thickening agent in the food industry [26].

Chemical structure of (A) alginate, (B) carrageenan, and (C) agar.

Images of some green, brown, and red seaweeds: (A) Codium sp.; (B) Dictyota sp.; and (C) Gracilaria sp. (A,B) images by John Turnbull and (C) by Rickard Zerpe, available at flickr.com.

The protein fraction found in seaweeds is also very variable depending on the seaweed type, the season, and place of collection [27,28]. 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) [29,30]. Thus, the nori variety is a red seaweed with up to 32.2% protein content [31], while green seaweeds such as some from the Ulva family contain up to 38.16% [32]. These proteins have an amino acid composition like that of legumes, glutamic acid and aspartic acid being the most abundant amino acids [33]. 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 [24]. 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 [33]. 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 [34,35]. The lipids of marine algae are mainly composed of polyunsaturated fatty acids, the content of which increases in species from cold climates [27,36].

Proximate composition of different seaweeds.

Pigmentation	Seaweed	Lipids	Carbohydrates	Protein	Ashes	Moisture	Reference
Green	Undaria pinnatifida	0.9 ± 0.1	32.4	23.8 ± 0.6	30.62 ± 0.25	11.77 ± 0.01	[27]
Green	Codium tormentosum	3.6 ± 0.2	32.8	18.8 ± 0.1	35.99 ± 0.48	9.0 ± 0.2	[27]
Red	Gracilaria gracilis	0.60 ± 0.01	46.6	20.2 ± 0.6	24.8 ± 0.03	7.99 ± 0.02	[27]
Red	Grateloupia turuturu	2.2 ± 0.1	43.2	22.5 ± 0.3	20.52 ± 0.01	11.68 ± 0.05	[27]
Red	Crassiphycus corneus	1.74 ± 0.05–1.93 ± 0.03	24.02 ± 2.23–23.55 ± 3.01	22.93 ± 0.16–21.27 ± 0.21	26.11 ± 0.06–34.16 ± 0.06	5.24 ± 0.12–4.30 ± 0.06	[37]
Green	Ulva fasciata	2.76 ± 0.34–2.37 ± 0.09	42.24 ± 0.70–40.91 ± 0.28	17.97 ± 0.15–11.42 ± 0.16	16.51 ± 0.85–20.89 ± 0.76	7.28 ± 0.34–10.29 ± 0.33	[37]
Brown	Sargassum vulgare	4.11 ± 0.03–4.02 ± 0.19	28.30 ± 0.32–39.07 ± 1.34	14.02 ± 0.24–10.32 ± 0.04	36.79 ± 0.76–30.09 ± 0.33	6.76 ± 0.06–4.53 ± 0.08	[37]
Brown	Alaria esculenta	1.30 ± 0.05	-	9.11 ± 0.57	24.56 ± 0.56	5.39 ± 0.05	[38]
Brown	Laminaria digitata	1.13 ± 0.05	-	5.31 ± 0.34	24.43 ± 0.03	6.81 ± 0.06	[38]
Brown	Rugulopteryx okamurae	11.63 ± 0.22	38.87 ± 0.40	9.93 ± 0.16	18.47 ± 0.35	13.48 ± 0.26	[39]
Brown	Dictyota dichotoma	4.70 ± 0.10	11.02 ± 0.09	4.32 ± 0.12	-	-	[40]

The issue of plastic pollution has been lingering for years, observing an increasing trend. Worldwide, plastic is being generated at 400 Mt per year, of which 90.4% is fossil-based, and only 9% of plastics are recycled. Most of the plastic produced (i.e., ~80%) ends up being discarded [41]. Depending on their size, plastic waste in nature can be classified as follows: macroplastics (>25 mm), mesoplastics (5–25 mm), microplastics (