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Algal bioplastics: A Sustainable Future

Have you ever wondered how plastics can be replaced with algae for a regenerative, plastic-free future? The Australian Government ambitions to make all packaging reusable, recyclable, or compostable by 2025. This paper discusses the current issues of plastic pollution and how algal bioplastics can be a promising candidate for a sustainable plastic-free solution.

What are the current issues of plastic pollution?

Since the inception of the first synthetic plastic, Bakelite, in 1907, plastic has been seldom utilised outside of the military (Gugliemi, 2017). The global annual plastic production proliferated exponentially, almost 230-fold over 70 years after 1950, reaching 460 million tonnes in 2019 (Ritchie & Roser, 2022). Being substantially affordable, lightweight, and durable, plastics have evolved into a necessary commodity in modern life, particularly in packaging, farming, fishing, and fashion industries (Bauman, 2019; UN Environment Programme, 2022). There has been a shift from the production of durable plastics towards single-use plastics. As of 2015, the world had produced approximately 8.3 billion tonnes of virgin plastic and generated 6.3 billion tonnes of plastic waste, of which 9% were recycled, 12% were incinerated, and the rest (79%) accumulated in landfills or the natural environment (Figure 1) (Geyer et al., 2017). The daunting trends and rate of plastic production will continue to exacerbate if we let nature take its course.

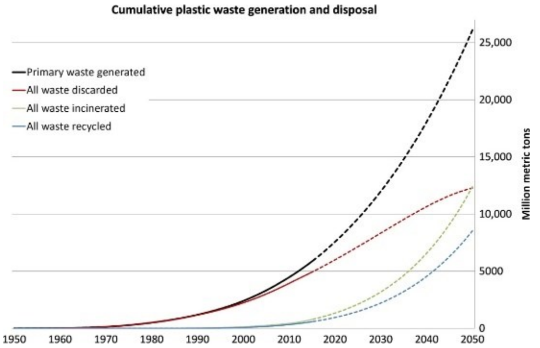


Figure 1. Cumulative plastic waste generation and disposal (Geyer et al., 2017)

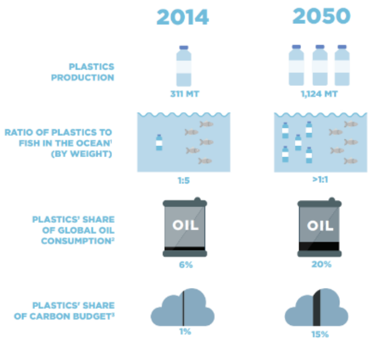


Figure 2. Forecast of growth in plastic production, externalities, oil consumption and carbon budget in a business-as-usual scenario. (World Economic Forum, 2016)

Nowadays, approximately 4–8% of the worldwide annual oil consumption goes towards plastic production. By 2050, plastics will account for 20% of total oil consumption under the business-as-usual scenario (World Economic Forum, 2016). Plastic derived from fossil fuels emits greenhouse gases over every phase of the plastic lifecycle, including extraction and transport, refining and manufacturing, and after-use and waste management. By 2050, oceans are forecasted to contain more plastics than fish by weight, and the cumulative greenhouse gas emissions from the plastic lifecycle will surpass 56 billion tonnes, constituting 10-15% of the annual global carbon budget (Figure 2) (Global Alliance for Incinerator Alternatives and Zero Waste Europe, 2018; Plastic-and-Climate-Executive-Summary, 2019). Apparently, the goal of the global community to restrict global temperature rise below 1.5°C is jeopardised by greenhouse gas emissions from the plastic lifecycle (Center of International Environmental Law, 2020).

As a result of the rising global demand for plastic products, including single-use plastics, severe plastic waste pollution has been a critical worldwide issue polluting our environment, specifically marine life (Global Alliance for Incinerator Alternatives and Zero Waste Europe, 2018). Reducing, reusing, and recycling have been frequently proposed as the predominant solutions to combat plastic waste. However, in reality, recycling is not effective enough and never will compensate for the overwhelming amount of plastics produced, given the fact that merely 9% of the 6.3 billion tonnes of plastic waste has ever been recycled since 1950, and the rest became pollution in oceans, landfills, dumpsites, and incinerator emissions, associating with high costs and the creation of toxic by-products that will last for millennia before decaying (Global Alliance for Incinerator Alternatives and Zero Waste Europe, 2018). Besides, the plastic waste recycling industry is not profitable enough and underwent an unprecedented economic disruption following China's import ban on foreign hazardous plastic waste trade in 2018 (Ritchie and Roser, 2022; Hook and Reed, 2018).

Plastic pollution was discovered in the world's remote areas, including the Antarctic and Cocos Islands, its deepest ocean floors at the Mariana Trench, and its highest summits at Mount Everest. 8 million pieces of plastic waste leak into the ocean every day. It was estimated in 2016 that single-use thin-film plastic constitutes 46%, or 5 million tonnes of the total of 11 million tonnes of virgin plastic penetrating the ocean annually. Not surprisingly, the projected annual plastic leakage into the ocean will nearly triple to 29 million tonnes by 2040 (Figure 3) (UN Environment Programme, 2022b; The Pew Charitable Trusts, n.d.). Ocean plastic pollution continues to relentlessly endanger ecosystems already negatively impacted by increased global warming, ocean acidification, and other stressors.

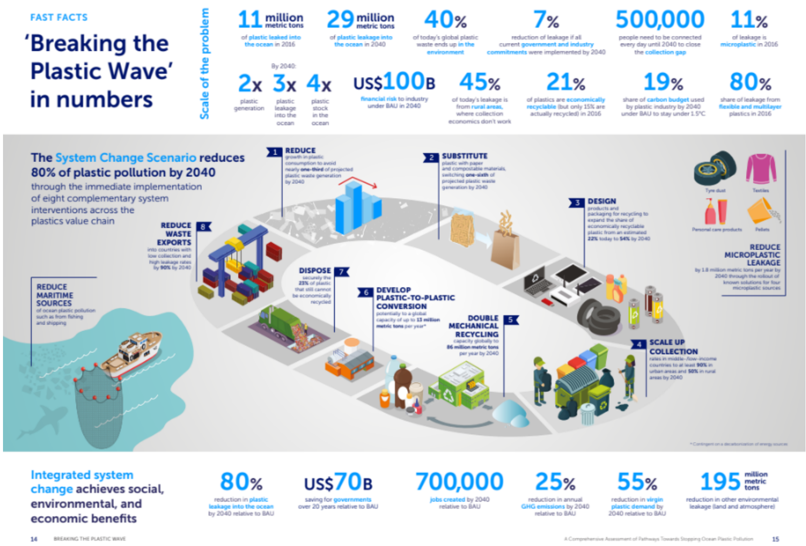


Figure 3. The scale of plastic pollution (The Pew Charitable Trusts, n.d.)

Further, plastic pollution is not merely a marine and climate issue but also threatens human health. Humans could have inevitably ingested tens of thousands of microplastics every year. Recent pioneering research in March 2022 discovered that microplastic pollution, particles as small as 0.0007mm, was detected in human blood and may pose detrimental damage to the functions of cells and organs (Carrington, 2022). 22 healthy blood samples were analysed to have found 17 (77%) contaminated with microplastics of which 50% were detected with polyethylene terephthalate (PET) from which drinking bottles were composed, 33% contained polystyrene primarily used in food packaging products, and 25% consisted of polyethylene commonly used in plastic bags (Carrington, 2022).

What is algal bioplastic?

Bioplastics are plastics that are made of renewable resources; they can be bio-based, biodegradable, or both (Table 1). Biodegradable plastic degrades in the environment over time. Compostable plastic can be decomposed into carbon dioxide, water, inorganic compounds, and nutrient-rich biomass by microorganisms in home compost or industrial compost facilities, leaving no toxic residue in the environment after degradation. All compostable material is biodegradable, but not all biodegradable material is compostable (Figure 4). Unlike conventional plastics, algal bioplastics biodegrade in the soil in only four to six weeks into microplastics. Replenishing life from sea to soil, algal bioplastics contribute to the circular economy and bioeconomy.

Table 1. Characteristics of different plastics and bioplastics (ABA, 2021)

Plastic type	Building Block	Example	Cost	Recyclable	Biodegradable
Conventional plastics	Fossil fuels	PE, PET, HDPE, PP	Low	Yes	No
Bio-based but not biodegradable	Biomass	Bio-based polyethylene (PE), polyethylene terephthalate (PET), bio-based technical performance polymers, such as polyamides (PA), or (partly) bio-based polyurethanes	Higher	Yes	No
Bio-based and biodegradable	Biomass	Polylactic acid (PLA), polyhydroxyalkanaoates (PHA), polybutylene succinate (PBS), and starch blends	Higher	No, and can contaminate recycling stream	Yes – some can be composted at home, others only through industrial composting facilities
Fossil-based and biodegradable	Biomass	PBAT and PCL	Higher	If added in high percentage could contaminate recycling stream	Yes – Home or Industrial Composting

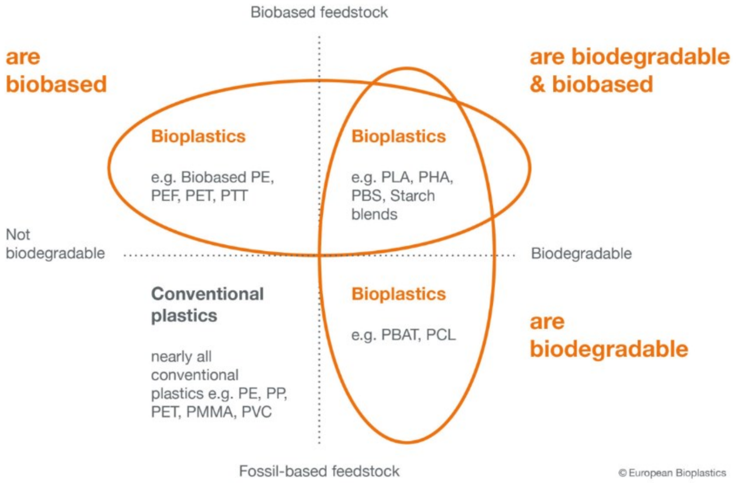


Figure 4. Material coordinate system for bioplastics (European Bioplastics,

What is seaweed?

Algae can be categorised into microalgae and macroalgae. According to their colours, three divisions of algae are Rhodophyta (red algae), Phaeophyta (brown algae), and Chlorophyta (green algae) (Table 2). Seaweed is not just a crispy green snack but essentially a marine macroalgae that demonstrates superior sustainability because it grows rapidly and abundantly, and does not require freshwater, land, pesticides, or fertiliser to cultivate. Algae are responsible for producing 70 to 90% of the Earth's total oxygen (Mouritsen, 2017; Zerocircle, 2023). While enriching marine biodiversity and nutrient cycling, seaweeds reduce and reverse ocean acidification and eutrophication. Along with boosting marine habitat provision, seaweed is a compelling carbon capture solution because it absorbs and sequesters 20 times more carbon dioxide from the atmosphere than terrestrial forests.

Seaweed is currently employed in many applications, including pharmaceuticals, cosmetics, food packaging, and so on (Figure 5). Seaweed is a prominent source of minerals; for instance, it contains potassium, which helps lower cholesterol and blood pressure, hence promoting cardiovascular health. Alginate can be used for wound dressing and is responsible for producing biofuels, including bio-butanol.

Table 2. Seaweed genera that are used to produce bioplastics. (Lim et al., 2021)

Type	Seaweed genera to make thin-film plastics
Red seaweeds	Kappaphycus (elkhorn sea moss), Eucheuma (agar), Gracilaria (red ogo), Porphyra (purple laver), Gelidium (umutgasari), Pterocladia
Green seaweeds	Ulva (sea lettuce), Codium (dead man's fingers) Enteromorpha (sea lettuce)
Brown seaweeds	Macrocystis (giant kelp), Laminaria (kelp), Ascophyllum (knotted wrack), Lessonia (kelp)

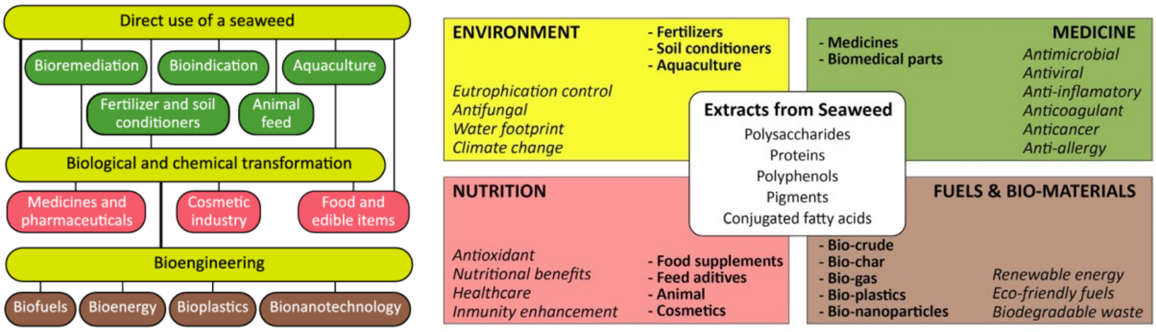


Figure 5. Applications of seaweed in biomanufacturing (Ditchburn and Carballeira, 2019)

What are the seaweed extraction methods?

Seaweed hydrocolloids, including polysaccharides, are extracted and manufactured into films (Table 3). Conventional extraction processes, involving washing, alkalisation, acidification, neutralisation, hot water filtration, precipitation, drying, and milling, are not effective in producing bioplastics (Figure 6) (Lim et al., 2021). Compared to petroleum-based plastics, these extraction methods produce low yields, are costly, time- and energy-consuming, and negatively impact the bioplastics' quality and properties (Lim et al., 2021).

Table 3. Polysaccharides that are available in red, brown, and green seaweeds (Abdul Khalil et al., 2016)

Polysaccharides	**Red seaweed**	**Brown seaweed**	**Green seaweed**
Agar	✓	-	-
Alginate	-	✓	-
Carrageenan	✓	-	-
Cellulose	✓	✓	✓
FlorideanStarch (α-1,4-bindingglucan)	✓	-	-
Fucoidan (sulphatedfucose)	-	✓	-
Laminarin (β-1, 3 glucan)	-	✓	-
Mannan	✓	-	-
Mannitol	-	✓	-
Porphyran	✓	-	-
Sargassam	-	✓	-
Sulphatedgalactans	✓	-	✓
Sulphuric acid polysaccharides	-	-	✓
Xylans	✓	-	✓

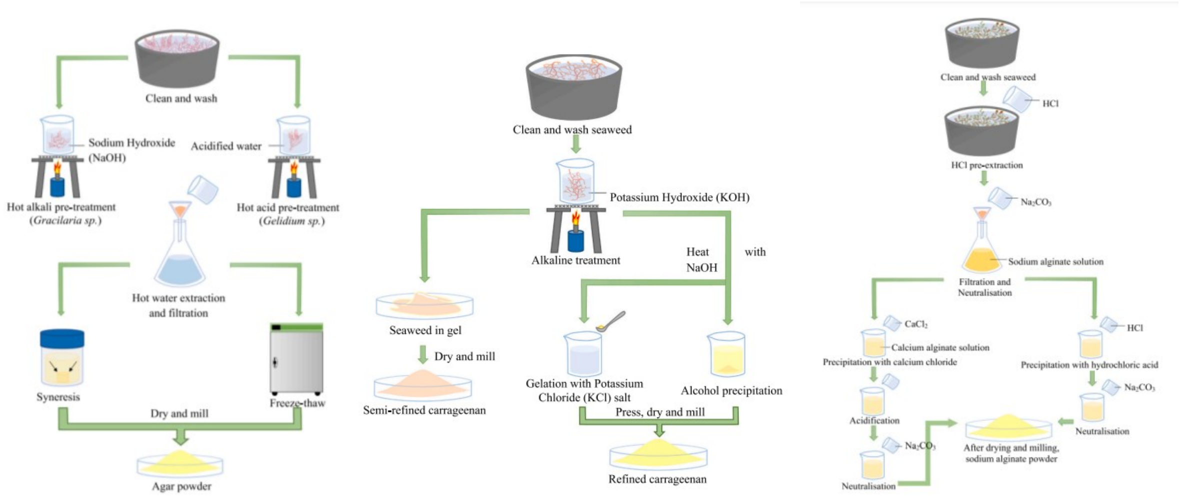


Figure 6. Convention agar (red seaweed), carrageenan (red seaweed), and alginate (brown seaweed) extraction process. (Lim et al., 2021)

On the contrary, seaweed bioplastics with green production methods hold a bright future with great potential and viability to supplant petroleum-based plastics. These green extraction processes include enzyme-assisted extraction, microwave-assisted extraction, photo-bleaching extraction, reactive extrusion, pressurised solvent extraction, supercritical fluid extraction, ultrasound-assisted extraction, and microbe fermentation (Lim et al., 2021). All these chemical-free synthesis methods present different strengths and weaknesses in producing bioplastics with specific characteristics and functions for different applications. A good example of a green production method is ULUU's microbial fermentation process using seaweed, seawater, and saltwater microbes (Kikken, 2022). The two-step procedure is the conversion of seaweed to sugars followed by microbial fermentation to produce natural polyesters (Figure 7). Unlike petroleum-based plastic, not only is seaweed itself a regenerative resource packed with green properties, but this manufacturing process is also a completely sustainable practice that reduces environmental impacts (Kikken, 2022).

Figure 7a. Machinery to conduct process of conversion and fermentation (Kikken, 2022)

Figure 7b. Fermented-seaweed powder (Kikken, 2022)

What are the properties and characteristics of seaweed bioplastics?

When developing novel seaweed bioplastic products, it is important to analyse and compare their properties and characteristics with those of petroleum-based plastics. The properties and characterisation are categorised into physical, optical, mechanical, morphological, thermal, antioxidant, antibacterial, and biodegradability (Table 4) (Lim et al., 2017).

Table 4. Properties and characterisation of seaweed bioplastic films. (Lim et al., 2017)

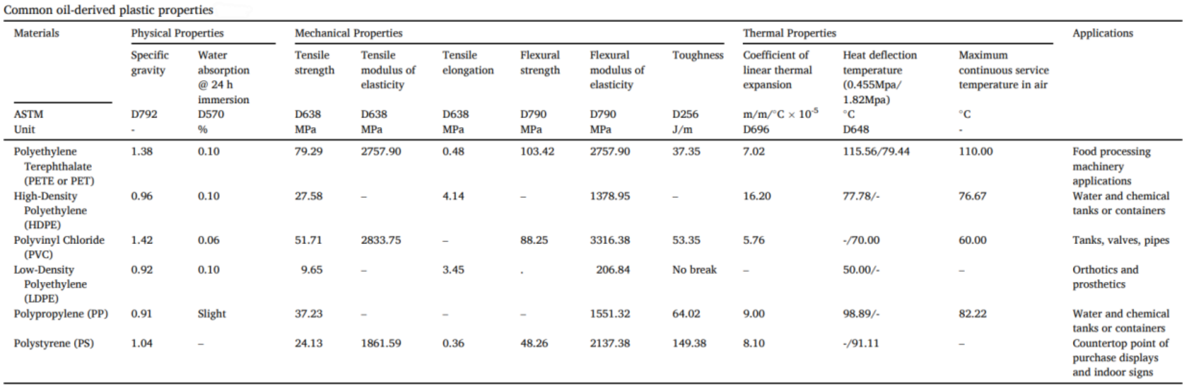
Properties and Characteristics	Specific properties to assess, purposes, and causes
Physical	- **Thickness:** ○ to calculate the mechanical and opacity. ○ to determine pest resistance, gas permeability, and mechanical properties. ○ affects by the molecular size, synthesis method, chemical structure, and aggregation between the seaweeds and plasticizers. - **Solubility:** ○ to indicate the biodegradability. ○ affects by the chemical nature of biopolymer and additives morphology or structure, and degree of cross-linking. - **Water vapor permeability (WVP):** ○ to determine whether suitable for food packaging. ○ to measure the ability of moisture to pass through. - **Water vapor transmission rate (WVTR):** ○ to indicate the barrier properties. ○ affects by the composition. - **Moisture content:** ○ to determine whether suitable for edible coating.

Optical	- **Colour properties:** o affects by the composition, molecular weight, and structure of extracts. - **UV capacity and the visible light barrier:** o affects by the composition and structure, affinity between polymers and plasticizers. - **Transparency:** o to determine the visual of a packaging where high transparency (low value) is preferred. - **Opacity:** o to measure colour properties can be measured via lightness (L*), redness (a*), yellowness (b*), whiteness index (WI), and total colour difference (ΔE) values. - **Light transmittance values:** o to determine the appearance of food. o to show the ability to protect the food against UV rays, by preventing light oxidative deterioration (loss of flavour, colour change, and loss of nutrients).
Mechanical	- **Tensile strength, elongation at break, and Young's Modulus:** o to indicate the strength, stretching ability or ductility, and stiffness of films. o affects by the seaweed source, surface charge, hydrophobicity, polymer chain length, type of plasticizer and percentage, and synthesis method.
Morphological	- **Fourier-transform infrared (FTIR) spectroscopy:** o to monitor the functional groups, structure, and interactions or bonding of molecules. - **Field Emission Scanning Electron Microscope (FESEM or SEM), Atomic force microscopy (AFM), X-ray diffraction analysis (XRD):** o to examine the microstructure, where it indicates the structure homogeneity, layer, cracks, holes or pores, smoothness or roughness, thickness, and surface.
Thermal	- **Thermal Gravimetric Analysis (TGA) and Differential Scanning Calorimetry (DSC):** o to determine the thermal stability of materials by supplying heat and causing the bond within the molecule to break.
Antioxidant	- **Total phenolic content** - **DPPH test:**

	○ to estimate the free radical scavenging activities of antioxidants. - **ABTS radical scavenging activities:** ○ to determine the activities from hydrogen donating and chain branching antioxidants. - **Ferric Reducing ability if plasma (FRAP):** ○ to determine the antioxidant properties of the film by acting as an electron donor reducing agent to free radicals.
Antibacterial	- **Inhibitory effects against bacteria including E. coli, L. monocytogenes, and S. Typhimurium:** ○ to calculate the bacteria count on the samples.
Biodegradability	- **Soil-burial test:** ○ to calculate the weight loss after days of soil-burial to determine biodegradability.

At this stage, having been extensively used for the past 70 years, petroleum-based plastics transcend seaweed bioplastics in terms of mechanical properties and functional versatility (Table 5). Following extraction, seaweed-based films usually consider the incorporation of other substances and casting. Additives, plasticisers, and cellulose are implemented in seaweed mixtures to enhance their properties and quality to suit certain applications (Tables 6 and 7). More innovators are joining to explore and invent novel green technologies using algae to reduce plastic waste.

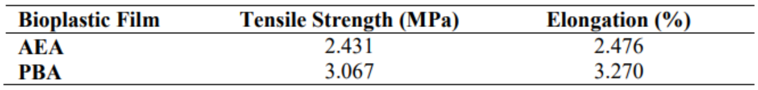
Table 5a. Common oil-derived plastic properties. (Lim et al., 2021)



Common oil-derived plastic properties

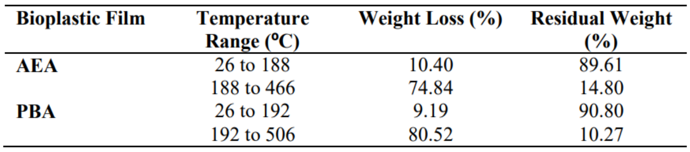
Materials	Physical Properties		Mechanical Properties						Thermal Properties			Applications
	Specific gravity	Water absorption @ 24 h immersion	Tensile strength	Tensile modulus of elasticity	Tensile elongation	Flexural strength	Flexural modulus of elasticity	Toughness	Coefficient of linear thermal expansion	Heat deflection temperature (0.455Mpa/ 1.82Mpa)	Maximum continuous service temperature in air	
ASTM	D792	D570	D638	D638	D638	D790	D790	D256	m/m/°C × 10^{-5}	°C	°C	
Unit	-	%	MPa	MPa	MPa	MPa	MPa	J/m	D696	D648	-	
Polyethylene Terephthalate (PETE or PET)	1.38	0.10	79.29	2757.90	0.48	103.42	2757.90	37.35	7.02	115.56/79.44	110.00	Food processing machinery applications
High-Density Polyethylene (HDPE)	0.96	0.10	27.58	–	4.14	–	1378.95	–	16.20	77.78/-	76.67	Water and chemical tanks or containers
Polyvinyl Chloride (PVC)	1.42	0.06	51.71	2833.75	–	88.25	3316.38	53.35	5.76	-/70.00	60.00	Tanks, valves, pipes
Low-Density Polyethylene (LDPE)	0.92	0.10	9.65	–	3.45	.	206.84	No break	–	50.00/-	–	Orthotics and prosthetics
Polypropylene (PP)	0.91	Slight	37.23	–	–	–	1551.32	64.02	9.00	98.89/-	82.22	Water and chemical tanks or containers
Polystyrene (PS)	1.04	–	24.13	1861.59	0.36	48.26	2137.38	149.38	8.10	-/91.11	–	Countertop point of purchase displays and indoor signs

Table 5b. Mechanical properties of two bioplastic films: alkali extracted agar (AEA) and photo bleached agar (PBA). (Hii et al. 2016)



Bioplastic Film	Tensile Strength (MPa)	Elongation (%)
AEA	2.431	2.476
PBA	3.067	3.270

Table 5c. Thermogravimetric analysis of two bioplastic films: alkali extracted agar (AEA) and photo bleached agar (PBA). (Hii et al. 2016)



Bioplastic Film	Temperature Range (°C)	Weight Loss (%)	Residual Weight (%)
AEA	26 to 188	10.40	89.61
	188 to 466	74.84	14.80
PBA	26 to 192	9.19	90.80
	192 to 506	80.52	10.27

Table 6. The incorporation of other components into seaweed matrix. (Abdul Khalil et al., 2016)

Seaweed	Other components/ plasticiser added	Film characteristics and improvements
Alginate	Calcium chloride / glycerin	The alginate film becomes water resistant from the immersion in CaCl2 solutions.
	Apple puree and essential oil	The film exhibits antibacterial activity. No adverse effect of the additives on water vapor and oxygen permeability.
	Sago starch and lemongrass oil / glycerol	The film exhibits antibacterial activity. The addition of lemongrass oil and glycerol decrease mechanical properties and increase water vapor permeability.
	Montmorilonite (MMT)	Film with low water solubility and water vapor permeability, and high mechanical properties.
	Cinnamon bark oil and soybean oil / glycerol	The addition of these oils improves film microstructure homogeneity, transparency, and antibacterial activity, while reducing film mechanical properties and water solubility.
	Kappa- and Iota-carrageenan / glycerol	The addition of K-carrageenan improves moisture barrier and overall tensile properties of film. The addition of I-carrageenan impairs those properties of film.
	Silver nanoparticles / gylcerol	The additions of silver particles improve the mechanical strength and water vapor barrier properties of film. This film exhibits a UV screening effect and strong antimicrobial activity.
Kappa-carrageenan	Grapefruit seed extract (GSE) / glycerol	Yellowish tint and great antibacterial activity film. The addition of GSE increases the moisture content, water vapor permeability and surface hydrophilicity, but decreases tensile strength and elastic modulus of film.
	Zataria multiflora essential oil & nanoclay / glycerol	The mechanical, antimicrobial and barrier properties of film are improved.
	Clay mineral & silver particles / glycerol	The nanocomposite film improves on the mechanical and water vapor barrier properties as well as antimicrobial activity
	Essential oil / glycerol & PEG	The addition of essential oil reduces water vapor permeability, tensile strength, moisture absorption and increases transparency of film.
	Chitin nanofibrils (CNF)	The film shows transparent, strong antibacterial activity and improved mechanical properties.

	Silver nanoparticles (Ag) & PVP / PEG	The incorporation of nanoparticles exhibits higher thermal stability, strength properties, antimicrobial activity, and lower swelling behaviour of film.
Agar	Arabinoxylan / glycerol	The addition of arabinoxylan improves moisture barrier efficiency but decreases mechanical properties of film.
	Starch / glycerol	The addition of starch degrades surface resistance to water wetting and mechanical properties of film.
	Silver nanoparticles (Ag)	The film exhibits good mechanical stability, water vapor and gas barrier as well as strong antimicrobial activity.
	Nanoclay / glycerin	Incorporation of clay (up to 10%) increases the tensile strength and decreases the water vapor permeability.
	Grapefruit seed extract (GSE)	The addition of GSE increases the colour, UV barrier, moisture content, water solubility and water vapor permeability, but decreases the surface hydrophobicity, tensile strength, and elastic modulus of film. The film exhibits distinctive antimicrobial activity.
	Banna powder and silver nanoparticles / gylcerol	The addition of banana powder increases the UV light absorption, water vapor barrier property and antioxidant activity, but decreases the mechanical properties of bilayer film. The composite film exhibits distinctive antimicrobial activity and mechanical properties.
	Fish gelatin and TiO2 nanoparticles	The addition of TiO2 decreases water vapor permeability and increases tensile strength, UV light barrier property, swelling ratio and moisture content of film.

Table 7. The performances and applications of various seaweed/cellulose composite films by casting. (Abdul Khalil et al., 2016)

Seaweed / Cellulose / Others	**Film characteristics, improvements & applications**
Alginate / NCC	Incorporation of NCC improves film mechanical properties (except elongation), water vapor permeability and thermal properties. **Application:** food packaging
Alginate / cellulose whickers / acerola puree and corn syrup	Incorporation of cellulose whiskers improves film tensile strength, elastic modulus, and water vapor barrier. **Application:** edible coating

Alginate / MFC / Chitosan-benzalkonium Chloride crosslinking with TPP	Incorporation of CMF/C–BC composite improves film antibacterial and strength properties. **Application:** food packaging
Alginate / NCC / Glycerol	Incorporation of up to 5% NCC increases tensile strength of film. **Application:** food packaging
Alginate / CMC / crosslinking with Graphene oxide	The composite exhibit high storage modulus, tensile strength and Young's modulus. **Application:** pharmaceutical devices
Alginate / Cellulose (19.0 µm–25 nm) /crosslinking with calcium	The composite shows excellent grease barrier properties & reduction in water vapor permeability (Except unmodified pulp). **Application:** packaging materials
Alginate / Carboxymethylated BC / crosslinking with calcium	The composite has dramatically improved in the swelling, thermal and mechanical properties. **Application:** wound dressings and skin tissue engineering
Alginate / BC / Silver sulfadiazine	The composite has an excellent antibacterial activities and good biocompatibility. **Application:** wound dressings
Alginate / CMC / Silver sulfadiazine	The film exhibits better swelling time. **Application:** hydrogel film
Alginate / NFC / Glycerol	Incorporation of CNF improves film water resistance and mechanical properties, decreases biodegradation time. **Application:** food packaging
Alginate / NCC	The hybrid hydrogels exhibited desired mechanical properties and improve resistance to biodegradation. **Application:** hydrogel film
Carrageenan / NFC / crosslinking with gelatin	Addition of CNF improves the tensile strength, water vapor transmission rate and oxygen transmission rate of film. **Application:** food packaging
Carrageenan / CMC / Nanoclay, glycerol	Hardness and adhesiveness increase as the polymer concentration increase. **Application:** soft gel capsules
Carrageenan / CMC / Acetic acid	The blend of kappa-carrageenan and cellulose derivatives exhibit good conductivity. **Application:** biopolymer electrolytes
Carrageenan / NCC / Glycerol	Incorporation of NCC (up to 4%) shows good dispersion, superior mechanical properties, and thermal stability of film. **Application:** packaging material
Agar / MFC / Chitosan methylisothiazolinone crosslinking with TPP	Incorporation of MFC/C–MIT composite enhances film tensile property and excellent antimicrobial activity. **Application:** biomaterial
Agar /NCC / Glycerol	Film transparency decreased. Addition of NCC improves film mechanical, thermal and water vapor barrier properties. **Application:** food packaging
Agar / NCC / Savory essential oil and Glycerol	Addition of savory oil decreases tensile strength, increases water vapor permeability and opacity, and improves antimicrobial property of film. **Application:** food packaging

Conclusion

Conventional plastic is a massive crisis to our planet. In recent years, with the joint effort of government initiatives, the development of new sources for edible packaging solutions and advancements in bioplastic technologies have contributed to the increase in popularity of algae bioplastic innovations. Algal bioplastics possess a bright future to supersede conventional petroleum-based plastics and play a vital role as one of the regenerative strategies to combat the staggering global plastic crisis. Ongoing research is warranted to develop algal bioplastics through green technologies to ensure that a circular economy is successfully created. While the development of algal bioplastics is still in its infancy, further studies and continuous efforts are necessary to fulfil the vision of eliminating petroleum-based plastics.

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