

*The Battle against Plastic Pollution; The Vanquish in Macroalgal Alginates: A review*

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## ***Abstract***

The persistent environmental threat posed by conventional plastics has catalyzed global efforts toward sustainable alternatives. This review explores the potential role of brown seaweed-derived alginates in bioplastic development, spotlighting their ecological compatibility and functional promise. It examines the structural and physicochemical attributes of alginates, positioning them as a viable polymer for bioplastic fabrication. Key insights include feasibility assessments of production at laboratory scale, degradation pathways influenced by microbial activity, and the broader ecological implications of bioplastic breakdown in marine and terrestrial environments. The review also outlines extraction and processing protocols for alginate-based bioplastics, offering a scalable framework for future innovation. Brown seaweed alginates thus emerge not only as a scientific solution but as a strategic contender in the global battle to vanquish plastic pollution.

## ***Introduction***

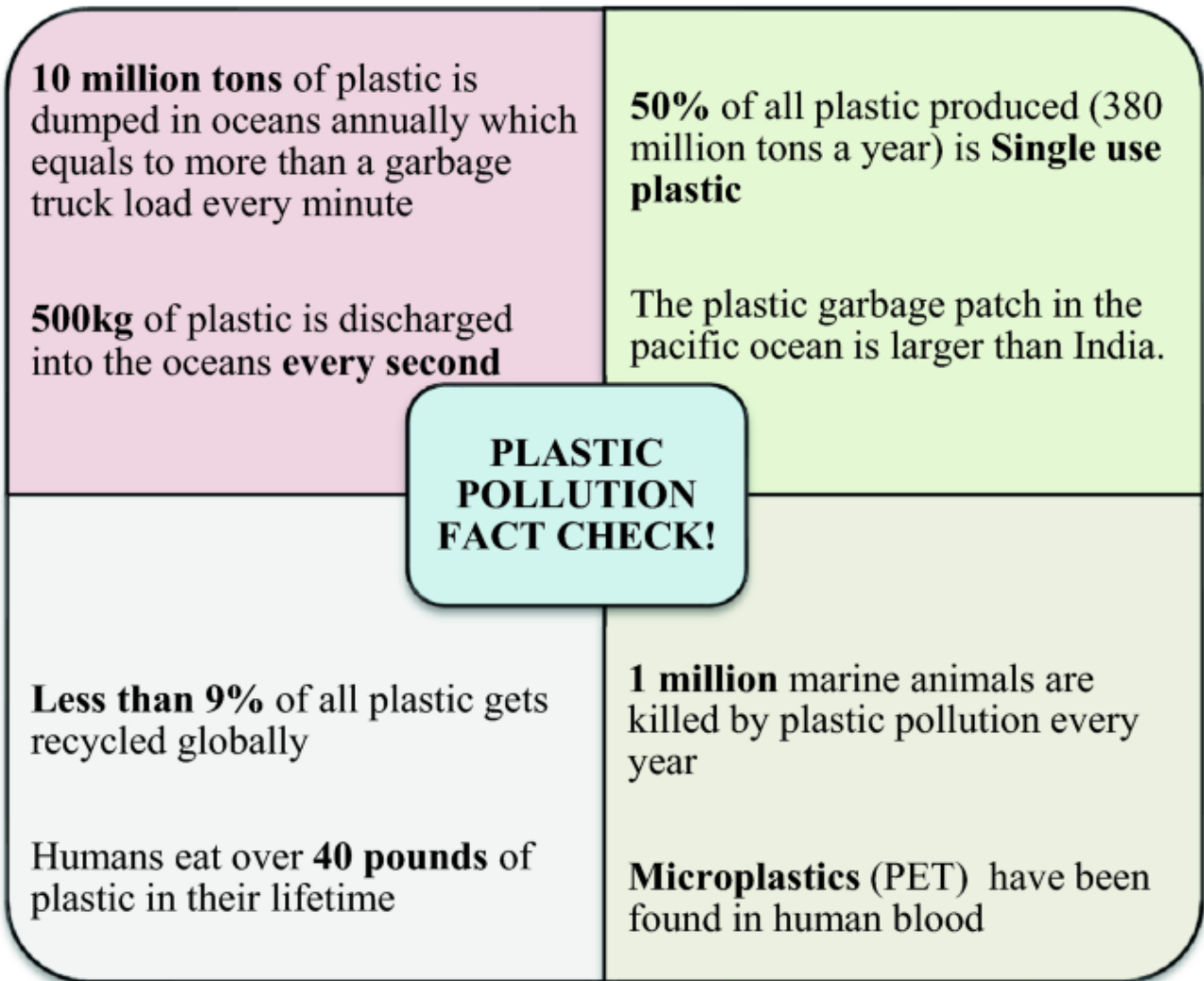
Packaging dominates the waste generated from plastics. Since its first synthesis in the 20th century, plastics have been a crucial centerpiece of society (Clayton *et al.*, 2021). Plastics are synthesized from hydrocarbon-based products (Pascoe, 2023). In 2015, 359 million tons of plastic were produced (Clayton *et al.*, 2021). However, with the advent of inflated consumerism, plastics are increasingly a menace every year. Globally, eight million metric tons of plastic waste leaked into the oceans in 2010, projected to increase to 53 million metric tons by 2030 (Clayton *et al.*, 2021). However, the majority of these plastics is single use packaging and eventually accumulates in the natural environment, breaking down into microplastics resulting in severe health concerns (Smith *et al.*, 2018). Single-use plastic packaging accounts for 36% of all plastic production, and packaging production has readily increased throughout the years (Disprose *et al.*, 2022). Additionally, plastic production emits approximately 390 million tons (Mt) of greenhouse gas (GHG) emissions per year. The two aforementioned menaces have put tremendous pressure on the environment and have been critical driving forces for development of alternative bio-based materials.

Due to global pollution with chemical plastics and their slow or non-biodegradability, eco-friendly alternatives are actively sought (Devadas *et al.*, 2021; Zanchetta *et al.*, 2021). In that regard, algal-based bioplastics represent plausible alternatives to chemical plastics. Mostly, macroalgae constitute hydrocolloids, which are hydrophilic macromolecules that exhibit great solubility when immersed in water. The viscosity and the ability to form 3D networks of polysaccharides found in seaweed (i.e., alginate, carrageenan, agar) play a crucial role in the development of bioplastics (Williams & Phillips, 2021). Bioplastics are plastics outsourced biologically (e.g., chitin, cellulose), synthesized similarly to petroleum based plastics, with the only difference being the bioplastic's source (e.g., agricultural waste, bacteria, fermentation), however, not all bioplastics are completely biodegradable, for instance, bio- polyethylene terephthalate is not biodegradable, despite the "bio" prefix (Pascoe, 2023). In the same vein, even if a bioplastic is deemed biodegradable, it does not mean the material can be disposed of anywhere. Most bioplastics require specific facilities with

proper conditions to degrade safely. As a result, while the bioplastic market grows, petroleum-based plastics are still predominately used. Thus, it is essential that the bioplastic industry research novel sustainable alternatives – ones that are compostable at home (Pascoe, 2023).

Bioplastics made from algae have become a hot topic in the emerging algae-based bioeconomy (Dang *et al.*, 2022). However, the expanding requirement for the production of bioplastics from algal source as a raw material will need a larger cultivation space to meet the increased demand for eco-friendly plastic. Bioplastic fabricated from sustainable macroalgae is a novel green production approach. It has been determined that brown seaweeds have a high carbohydrate content as promising feedstocks alternative to produce biodegradable plastics. They have greater capacity as a bioplastic source as they are planted in seawater instead of land, their greater biomass yield, rapid reproduction, ease of upkeep in various settings, and affordability (Lomartire *et al.*, 2022). Bio-based plastics are currently being developed to replace traditional petroleum plastics as these materials are natural carbon sinks, absorbing CO<sub>2</sub> from the atmosphere and emitting up to 30% less GHG emissions-(Vanderreydt *et al.*, 2021) while decomposing much faster in the natural environment over synthetic plastics through aerobic degradation or anaerobic fermentation (Bátori *et al.*, 2018; Roy Chong *et al.*, 2018; Vardar *et al.*, 2022).

This review addresses the environmental challenges posed by conventional plastics and positions brown seaweed alginates as a viable alternative. It explores the structural and functional merits of alginates for polymer applications, evaluates the lab-scale feasibility of bioplastic production, and examines their microbial degradability. Furthermore, it investigates the ecological implications of bioplastic breakdown and provides practical extraction and fabrication protocols to support scalable innovation.



*Fig 1: Plastic Pollution facts (Neha and Navneeta, 2022)*

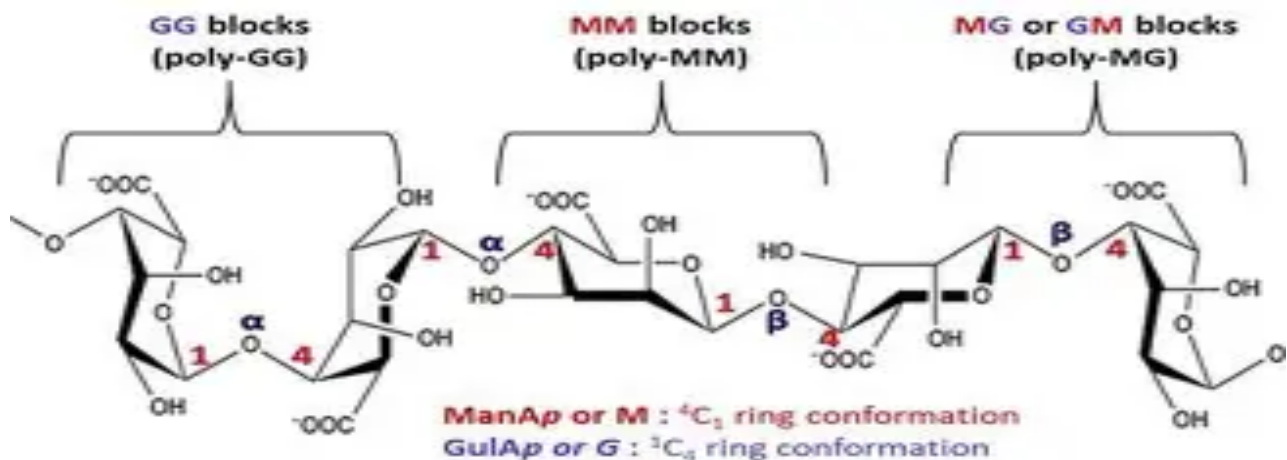
### **Alginates**

Alginates are naturally occurring indigestible polysaccharides located in the cell wall and in the matrix of brown seaweeds (Rinaudo,2007), and it is the main polysaccharides found in the cell wall of brown algae, representing approximately 40% of the dry matter of seaweed (Łabowska *et al.*, 2019). However, some bacteria such as *Azotobacter vinelandii* or mucoid strains of *Pseudomonas aeruginosa* also synthesize alginate-like polymers as exopolysaccharide (i.e., extracellular polymeric substances, EPSs) (Emmerishs *et al.*, 2004). In contrast, bacterial alginates have O-acetyl groups, but absence in structure of algal alginates (Davidson, *et al.*, 1997). Additionally, bacterial alginates have higher molecular weights compared to the algal

polymers.

Alginate production by bacteria was first reported in the opportunistic pathogen *Pseudomonas aeruginosa* and then in three nonpathogenic species of *Pseudomonas* including *P. mendocina*, *P. putida* and *P. fluorescens*. Soil bacteria (*Azotobacter vinelandii*) is very suitable for the production of bacterial alginates (Clementi *et al.*, 1995).

Alginate is a linear copolymer constituted by (1 → 4) linked β D-mannuronic acid (M) and α L-guluronic acid (G) residues randomly distributed along the carbohydrate chains (Usov & Zelinsky, 2013). These uronic acids can form homogeneous blockchains of MM (M blocks) or GG units (G blocks) and chains with alternate blocks of mannuronic acid and guluronic acid (MG blocks) (Makarova *et al.*, 2023). **Fig 2:** (Roya *et al.*, 2022)



Alginate was discovered and its extraction protocol was patented by Dr. E.C.C. Stanford in 1881 (Patent No. 142) (Draget, 2009). Alginates (i.e., sodium alginate (E401), potassium alginate (E402), ammonium alginate (E403), and calcium alginate (E404)) are monovalent salts of alginic acid (E400) (Younes *et al.*, 2017; Lu *et al.*, 2006). Alginic acid and calcium alginate are insoluble in water while sodium alginate, potassium alginate, and ammonium alginate are water-soluble polymers (Lu *et al.*, 2006). They have a limited solubility at low pH values (USDA, 2018). Sodium alginate is the most common salt of alginate (Yoo *et al.*, 2011).

Commercial alginates are produced and refined from various genera of brown alga, mainly *Laminaria hyperborean*, *Macrocystis pyrifera*, *Ascophyllum nodosum*; to a lesser extent *Laminaria digitate*, *Laminaria japonica*, *Ecklonia maxima*, *Lesonia negrescens*, *Sargassum sp.* (Fernando *et al.*, 2020) and mostly characterized by its biodegradability, biocompatibility, non-toxicity, and high viscosity, as well as its wide range of valuable biotechnological properties. These economic viable algae are cultivated at commercial scale under variable environmental vagaries in different type of land-based bio-reactor or in the open sea and processed for diverse use (Kumar *et al.*, 2011). Moreover, it is estimated that 23,000 tons of alginates are produced from about 85,000 tons of algae annually (Bertagnolli *et al.*, 2014). Commercial brown macroalgae such as *Laminaria*, *Ecklonia*, *Macrocystis*, and to some extent *Sargassum* contain valuable sodium alginates.

Currently, alginate is one of the most versatile and useful biopolymers utilized in many industries, due to its ability to form gels in the presence of certain divalent cations (e.g., Ca<sup>2+</sup>) through a cross-linking reaction and forming an egg-box structure (Hu *et al.*, 2021). Therefore, alginate has been the subject of research in various fields related to the exploitation of marine biological resources, and it has been found that the structure and composition of alginate significantly influence its biological activity (Li *et al.*, 2023). Nevertheless, the quantity and quality of the alginate highly depend on several factors such as species, age, type, and part of the tissues, environmental conditions, the season of harvest, and the extraction method (Saji *et al.*, 2022).

### ***Is bioplastic production from macrolage feasible yet?***

Polymers from algae are extracted by different methods and are cost-effective at industrial scale (Carina *et al.*, 2021; Rashedy *et al.*, 2021). Traditionally, alginate films are produced via solvent casting (Avella *et al.*, 2007; Jost *et al.*, 2014), a method suitable for laboratory-scale research but poorly suited for industrial-scale production due to limitations such as non-uniform thickness,

slow drying times, and poor blend compatibility (Gao *et al.*, 2017; Jeevahan *et al.*, 2020; Mortalò *et al.*, 2023). Additionally, the third generation bioplastics derived from algal biomass and biomaterials offer innovative feedstock however; this potential is still at the cradle stage of development (Coppola *et al.*, 2021).

Primitively, economic and market potential of bioplastic produced from macroalgae is still not feasible, as it has been reported by Folino *et al.* (2020) that production cost is 2 to 5 times more expensive than conventional plastics, mostly attributed to high R&D cost at commercial scale, and high cost of raw materials. Although there has been positive public disposition towards sustainability and an informed willingness to purchase an eco-friendly products, however there is still limited evidence to suggest that the purchase of these products has increased as reported by Dilkes-Hoffman *et al.* (2019). Therefore, there is still a need to develop a production approach that is cost effective to force down the production cost of bioplastic from macroalgae, consequently driving the bioplastic market growth.

### ***Bio-degradation of Bioplastics.***

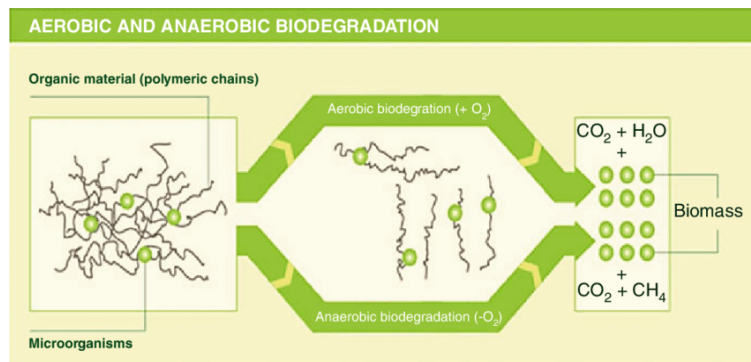
Biodegradation is a promising method for tackling global environmental plastic menace, which involves the breakdown of polymers by microbial enzymes (Fachrul *et al.*, 2021).

Biodegradation usually involves two methods, one is aerobic and another is anaerobic type (Pathak and Navneet, 2017). Aerobic biodegradation utilizes oxygen and degrades organic materials into carbon-dioxide, whereas anaerobic biodegradation utilizes organic and CH<sub>4</sub>.

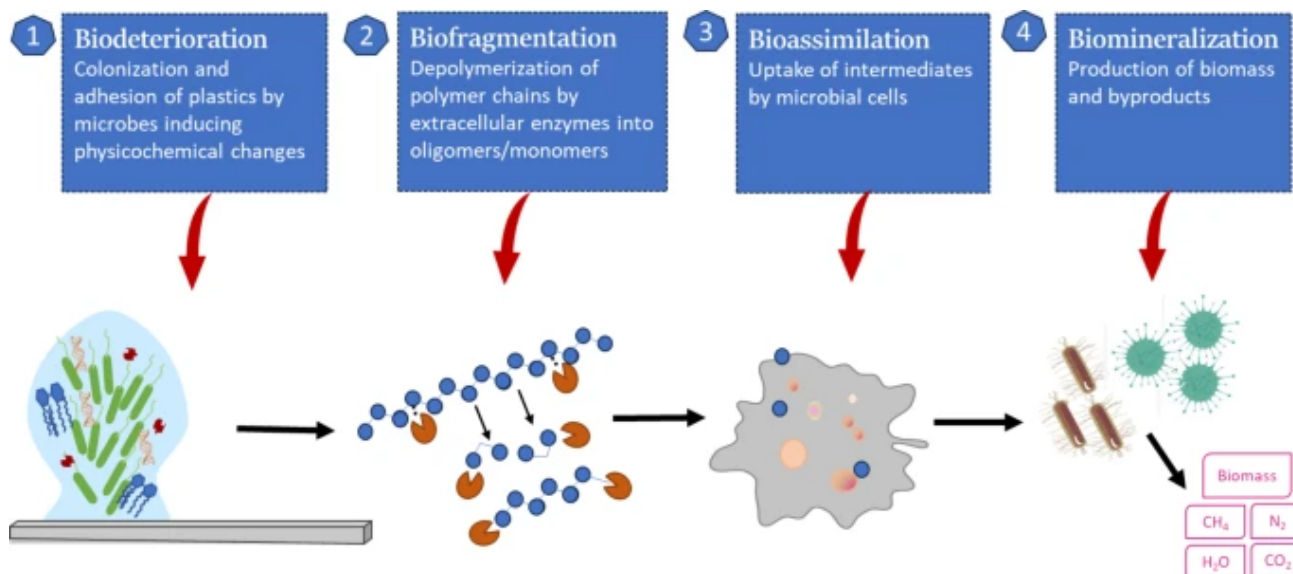
Various microorganisms, especially bacteria, produce extra or intracellular enzymes that degrade plastics (Okamoto *et al.*, 2003; Agrawal and Singh, 2016; Chaurasia, 2020; Begum *et al.*, 2015; Hedayati, 2022). Besides enzymatic activity, microbes contribute chemical and physical actions to the process (Jamee and Siddique, 2019). The resulting degradation products; monomers, dimers, and oligomers serve as microbial energy sources, with carbon dioxide and

water often forming as end products (Siracusa, 2019; Urbanek *et al.*, 2018; Hedayati, 2022). These transformations alter polymer structure, mechanical strength, and functional group composition (Arutchlevi *et al.*, 2008). However, beyond microbial degradation, plastic degradation can also happen through photooxidation, chemical degradation, and thermal degradation (Mahdiyah and Mukti 2013). The biodegradation of polymers consists of 3 important steps: 1) Biodeterioration, which is the modification of mechanical, chemical, and physical properties of the polymer due to the growth of microorganisms on or inside the surface of the polymers. 2) Biofragmentation, which is the conversion of polymers to oligomers and monomers by the action of microorganisms, and 3) Bioassimilation & Biomineralization where microorganisms are supplied by necessary carbon, energy and nutrient sources from the fragmentation of polymers and convert carbon of plastic to CO<sub>2</sub>, water and biomass (Lucas *et al.*, 2008). Biomineralization is the final metabolic process of plastic polymers by which biomass is transformed to oxidized metabolites such as CO<sub>2</sub>, N<sub>2</sub>, CH<sub>4</sub>, and H<sub>2</sub>O (Ho *et al.*, 2018). The mineralization process, whether aerobic or anaerobic, requires the involvement of several different enzymes such as esterases, lipases, cutinases, peroxidases, and laccases (Alshehrei, 2017)

The important factors that affect the plastic's biodegradation in the environment are the chemical structure, the polymer chain, crystallinity and the complexity of polymer formula. In fact, the specific functional groups are selected by enzymes and can be processed. Generally, polymers with a shorter chain, more amorphous part, and less complex formula are more susceptible to biodegradation by microorganisms. Moreover, the environment, in which the polymers are placed or disposed of, plays as a key factor for their biodegradation. The pH (Optimal range: 5.0-7.5), temperature (25°C – 40°C), moisture and the oxygen content are among the most significant environmental factors that must be considered in biodegradation of polymers (Massardier-Nageotte *et al.*, 2006, Kale *et al.*, 2007b).



**Fig 3:** Mechanism of Aerobic and Anaerobic Biodegradation (Nofal, R. M. 2022)



**Fig 4:** Mechanism of biodegradation of biodegradable plastics (Payanthoth *et al.*, 2024)

### ***Environmental implications of Bioplastic biodegradation***

Primarily, conventional plastics induce adverse effects, including reductions in soil nutrients, microbial diversity, bioturbation, enzyme activity, easily decomposable carbon, and microbial biomass carbon in plant debris (Iqbal *et al.*, 2024; Li *et al.*, 2024). In contrast, BPs resulted in beneficial effects, such as an increase in enzyme activity, microbial biomass carbon, and easily decomposable carbon (Tosin *et al.*, 2019; Meng *et al.*, 2023). Thus, BPs are believed to improve the overall soil quality and nutrient cycling during biodegradation. For instance, Goldberger *et al.* highlighted the capacity of BDMs to degrade effectively in soil or composting environments,

which can enhance soil quality (Goldberger *et al.*, 2019). In addition, adding 10% PHBV increased microbial biomass carbon and DOC by 12 and 54 times, respectively, while microbial biomass nitrogen rose by 45% and dissolved organic nitrogen decreased by 66% compared to control soil (Zhou *et al.*, 2021). Although bioplastic degradation benefits nitrogen cycling in soil, their impact on freshwater environments can disrupt nutrient cycling and harm ecosystem health.

### ***Protocols for lab. Scale production of Bioplastics from Macroalgae alginates.***

#### ***Algae collection and Sampling***

The brown macroalgal biomass will either be collected from a captive or cultivated source and a preliminary identification of the algal sample to the spp. level will be carried out using identification keys 1.

#### ***Washing and Pre-treatment***

The species collected will be washed using distilled water to remove salt residues, sands, impurities and epiphytes from the macroalgal biomass. The washed algae will be subjected to two types of pre- treatments; **Pre-treatment A** aimed at breaking the cell wall and to improve the mass transfer while **pre-treatment B** will prevent co-extraction of other bioactive compounds with similar solubility (Dobrin'ci'c *et al.*, 2020). Subsequently, the wet weight of the seaweed biomass will be weighed using a weigh balance.

#### ***Pre-treatment A (Drying and Milling)***

As recommended by Chemat *et al.* (2017), hot-air drying (40-60<sup>0</sup>c) will be applied on the algal biomass to modify the cell membrane permeability, accelerate mass transfer, prevent microbial growth, and facilitate transport and storage (Ummat *et al.*, 2021). Subsequently, the dried seaweed will be milled into powders with a particle size of around 0.5 mm-1 mm, to increase the surface area, thus increasing the extraction efficiency. The dry weight of the algal biomass will

be measured consequently.

### ***Pre-treatment B (Bleaching)***

As proposed by Gao *et al.* (2018), Fenton reaction (7.4Mm FeSO<sub>4</sub>) dissolved in H<sub>2</sub>O, will be employed due to reduced water consumption, high extraction yield, mannuronate content reduction, and approximately (~85%) decrease in viscosity. Although plausible alternatives are *Acetone* (Fawzy *et al.*, 2021), and *Ethanol* (Trica *et al.*, 2019)

### ***Acid Treatment***

Acid treatment will be carried out to remove non-target compounds such as polyphenols, mannitol, and other easily extractable polysaccharides (e.g., laminarins, fucoidan), as well as other low molecular weight compounds. Similarly, acid will also eliminate polyvalent cations, such as Ca<sup>2+</sup> and Mg<sup>2+</sup> from the alginate matrix by converting alginate from the salt form into alginic acid (Peteiro, 2018)

In line with Sari-chimayisen *et al.* (2016) work on *Sargassum vulgare*, ***0.1M dilute H<sub>2</sub>SO<sub>4</sub>, PH <2, 3hrs at 50°C*** with biomass loading ratio 1:20 (w/v), dry weight seaweed biomass to acid solution) (Trica *et al.*, 2019) will be used to remove non-target compounds, improve extraction yield, aiding the disruption of cell wall and thus the release of the polysaccharides (Dobrinčić *et al.*, 2020).

### ***Alkaline Extraction***

Although alkali pre-treatment of seaweed is less popular than acid pre-treatment, it has been reported in several patents in the 1960s as well as recent research papers (Hernández-Carmona *et al.*, 1998; Giyatmi *et al.*, 2021). The preliminary target for the alkali pre-treatment is to degrade the seaweed cell wall to enable the subsequent alginate extraction.

Due to the heterogeneity of brown algae, a consensus on the best pH range cannot be applied for all brown algae species, however Tiemi *et al.* (2022) reported a high yield of alginate (~45.8%) *Sargassum cymosum* with 2% Na<sub>2</sub>CO<sub>3</sub> at P<sup>H</sup> 10 for 2hrs at biomass loading ratio 1:20 (w/v, dry weight seaweed biomass to alkaline solution)

### ***Precipitation***

Barium Chloride (BaCl<sub>2</sub>) solution (0.1-0.5m) will be used in the precipitation process due to Barium ions ((Ba<sup>2+</sup>) high affinity and selectivity towards alginate, It will be added slowly to the alginate extract while stirring (30-60 minutes) until a gel is formed. Subsequently, the Barium alginate gel will be suspended in NaCl or Na<sub>2</sub>CO<sub>3</sub> solution. This will exchange Ba<sup>2+</sup> for Na<sup>+</sup>, converting the gel into sodium alginate and precipitated with Alcohol or Isopropanol (1.1 v/v or higher) (Pawar and Edgar, 2012). The gel will be stirred within 1-2hrs, then filtered or centrifuged to recover the Sodium Alginate.

### ***Drying and Milling***

Using an oven, the alginate precipitate will be dried at 55°C between 12-16 hr until a crisp and light product is obtained. Subsequently, the alginate obtained will be pulverized into fine powder (~0.5- 6mm/250mm) to optimize solubility (Hernández-Carmona *et al.*, 2002)

### **Alginate bioplastic production protocols**

### ***Wet formation or solvent casting***

This technique is geared towards evaporating water-containing biopolymers to dry the solution (Anjani et al., 2018)

### ***Polymer dissolution***

The alginate polymer will be dissolved in a suitable solvent (warm distilled water, 40-50<sup>0</sup>C) to speed up hydration and ii) stirred vigorously to avoid clumping and it may require the addition of other compounds (co-solvents such as glycerol, as a plasticizer or ethanol for precipitation).

***Homogenization:*** The solution will be poured into a suitable mold or a Teflon-coated plate, allowed to dry, and, subsequently, the film obtained will be separated as described by (Prakoso *et al.*, 2023, Kumar *et al.*, 2022)

## References

- Abka-Khajouei, R., Tounsi, L., Shahabi, N., Patel, A. K., Abdelkafi, S., & Michaud, P. (2022). Structures, properties and applications of alginates. *Marine drugs*, 20(6), 364.
- Agrawal P, Singh RK (2016) Breaking down of polyethylene by Pseudomonas species. *Int J Sci Eng Res* 7(3):124–127.
- Alshehrei F (2017) Biodegradation of synthetic and natural plastic by microorganisms. *J Appl Environ Microbiol* 5:8–19
- Avella, M., Di Pace, E., Immirzi, B., Impallomeni, G., Malinconico, M., & Santagata, G. (2007). Addition of glycerol plasticizer to seaweeds derived alginates: Influence of microstructure on chemical–physical properties. *Carbohydrate polymers*, 69(3), 503-511.
- B.-T. Dang, X.-T. Bui, D.P.H. Tran, H.H. Ngo, L.D. Nghiem, P.-T. Nguyen, H. H. Nguyen, C. Lin, K.Y.A. Lin, S. Varjani, Current application of algae derivatives for bioplastic production: a review, *Bioresour. Technol.* 347 (2022), 126698, <https://doi.org/10.1016/j.biortech.2022.126698>.
- Begum MA, Varalakshmi B, Umamageswari K (2015) Biodegradation of polythene bag using bacteria isolated from soil. *Int J Curr Microbiol App Sci* 4(11):674–680
- Bertagnolli, C., Espindola, A. P. D., Kleinübing, S. J., Tasic, L., & da Silva, M. G. C. (2014). Sargassum filipendula alginate from Brazil: Seasonal influence and characteristics. *Carbohydrate polymers*, 111, 619-623.
- Carina, D., Sharma, S., Jaiswal, A.K., Jaiswal, S., 2021. Seaweeds polysaccharides in active food packaging: a review of recent progress. *Trends Food Sci. Technol.* 110, 559–572. <https://doi.org/10.1016/J.TIFS.2021.02.022>.
- Chaurasia M (2020) Analytical review on biodegradation of plastics. *eLifePress* 1(1):1–8.
- Clayton, A. C., et al. “Policy responses to reduce single-use plastic marine pollution in the Caribbean.” *Marine Pollution Bulletin*, vol. 162, Jan. 2021. <https://doi.org/10.1016/j.marpolbul.2021.112111>.

org/10.1016/j.marpolbul.2020.111833. 2.

Clementi, F.; Fantozzi, P.; Mancini, F.; Moresi, M. Optimal Conditions for Alginate Production

by *Azotobacter Vinelandii*. *Enzym. Microb. Technol.* 1995, 17, 983–

988. [https://doi.org/10.1016/0141-0229\(95\)00007-0](https://doi.org/10.1016/0141-0229(95)00007-0).

Coppola, G., Gaudio, M. T., Lopresto, C. G., Calabro, V., Curcio, S., & Chakraborty, S. (2021).

Bioplastic from renewable biomass: a facile solution for a greener environment. *Earth systems and environment*, 5(2), 231-251.

Davidson, I. W., Sutherland, I. W., & Lawson, C. J. (1977). Localization of O-acetyl groups of

bacterial alginate. *Microbiology*, 98(2), 603-606.

Devadas, V. V., Khoo, K. S., Chia, W. Y., Chew, K. W., Munawaroh, H. S. H., Lam, M. K., ... &

Show, P. L. (2021). Algae biopolymer towards sustainable circular economy. *Bioresource technology*, 325, 124702.

Dilkes-Hoffman, L., Ashworth, P., Laycock, B., Pratt, S., & Lant, P. (2019). Public attitudes

towards bioplastics—knowledge, perception and end-of-life management. *Resources, Conservation and Recycling*, 151, 104479.

Diprose, G., et al. “Reducing Single Use Packaging and Moving up the Waste Hierarchy.”

Kōtuitui: New Zealand Journal of Social Sciences Online, vol. 18, no. 3, Dec. 2022.

<https://doi.org/10.1080/1177083x.2022.2154230>.

Draget, K.I. Alginates. In *Handbook of Hydrocolloids*, 2nd ed.; Woodhead Publishing: Sarston,

UK, 2009; pp. 807–828.

Evans, L. R., & Linker, A. (1973). Production and characterization of the slime polysaccharide

of *Pseudomonas aeruginosa*. *Journal of bacteriology*, 116(2), 915-924.

Fachrul MF, Rinanti A, Salmiat ST (2021) Degradation of polyethylene plastic waste by

indigenous microbial consortium and fungi. *Indones J Urb Environ Technol* 5(1):86–103.

- Fawzy, M.A.; Gomaa, M. Optimization of citric acid treatment for the sequential extraction of fucoidan and alginate from *Sargassum latifolium* and their potential antioxidant and Fe(III) chelation properties. *J. Appl. Phycol.* **2021**, *33*, 2523–2535.
- Fernando, I. P. S., Lee, W., Han, E. J., & Ahn, G. (2020). Alginate-based nanomaterials: Fabrication techniques, properties, and applications. *Chemical Engineering Journal*, *391*, 123823.
- Folino, A., Fazzino, F., & Komilis, D. (2020). Preliminary evaluation of the anaerobic biodegradability of three biobased materials used for the production of disposable plastics. *Journal of hazardous materials*, *390*, 121653.
- Gao, C., Pollet, E., & Avérous, L. (2017). Properties of glycerol-plasticized alginate films obtained by thermo-mechanical mixing. *Food hydrocolloids*, *63*, 414-420.
- Giyatmi, G.; Irianto, H.E.; Anggoro, B.; Nurhayati; Fransiska, D. Use of basil leaf ethanol extract in alginate base edible film. *J. Phys. Conf. Ser.* **2021**, *1933*, 012001.
- Glicksman, M. Utilization of Seaweed Hydrocolloids in the Food Industry. In Twelfth International Seaweed Symposium; Springer Netherlands: Dordrecht, The Netherlands, 1987; pp. 31–47.
- Goldberger JR, DeVetter LW, Dentzman KE (2019) Polyethylene and biodegradable plastic mulches for strawberry production in the United States: experiences and opinions of growers in three regions. *HortTechnology* 29:619–628
- Hedayati A (2022) Microplastics in marine ecosystems. *Sustain Aquat Res* 1(2):63–73.
- Hernandez-Carmona, G.; McHugh, D.J.; Arvizu-Higuera, D.L.; Rodríguez-Montesinos, Y.E. Pilot plant scale extraction of alginates from *Macrocystis pyrifera* 4. Conversion of alginic acid to sodium alginate, drying and milling. *J. Appl. Phycol.* **2002**, *14*, 445–451
- Hernández-Carmona, G.; McHugh, D.J.; Arvizu-Higuera, D.L.; Rodríguez-Montesinos, Y.E.

- Pilot plant scale extraction of alginate from *Macrocystis pyrifera*. 1. Effect of pre-extraction treatments on yield and quality of alginate. *Environ. Boil. Fishes* **1998**, *10*, 507–513.
- Ho BT, Roberts TK, Lucas S (2018) An overview on biodegradation of polystyrene and modified polystyrene: the microbial approach. *Crit Rev Biotechnol* 38:308–320
- Hu, F., Cao, S., Li, Q., Zhu, B., & Yao, Z. (2021). Construction and biochemical characterization of a novel hybrid alginate lyase with high activity by module recombination to prepare alginate oligosaccharides. *International Journal of Biological Macromolecules*, *166*, 1272-1279.
- I. Vanderreydt, T. Rommens, A. Tenhunen, L. Mortensen and I. Tange, *Greenhouse gas emissions and natural capital implications of plastics (including biobased plastics)*, European Topic Centre Waste and Materials in a Green Economy, European Union, 2021
- Iqbal B, Zhao X, Khan KY, Javed Q, Nazar M, Khan I, Zhao X, Li G, Du D (2024) Microplastics meet invasive plants: unraveling the ecological hazards to agroecosystems. *Sci Total Environ* 906:167756 11 Li Y, Yan Q, Wang J, Shao MA, Li Z, Jia H (2024) Biodegradable plastics fragments induce positive effects on the decomposition of soil organic matter. *J Hazard Mater* 468:133820
- J. W. Roy Chong, X. Tan, K. S. Khoo, H. S. Ng, W. Jonglertjunya, G. Y. Yew and P. L. Show, *Environ. Res.*, 2022, **206**, 112620
- Jamee R, Siddique R (2019) Biodegradation of synthetic dyes of textile effluent by microorganisms: an environmentally and economically sustainable approach. *Eur J Microbiol Immunol* 9(4):114–118
- Jeevahan, J. J., Chandrasekaran, M., Venkatesan, S. P., Sriram, V., Joseph, G. B., Mageshwaran, G., & Durairaj, R. B. (2020). Scaling up difficulties and commercial aspects of edible films for food packaging: A review. *Trends in Food Science & Technology*, *100*, 210-222.
- Jost, V., Kobsik, K., Schmid, M., & Noller, K. (2014). Influence of plasticiser on the barrier,

mechanical and grease resistance properties of alginate cast films. *Carbohydrate polymers*, 110, 309-319.

Kumar, M. S., Yaakob, Z., & Siddaramaiah. (2011). Biobased materials in food packaging applications. *Handbook of bioplastics and biocomposites engineering applications*, 121-159.

Łabowska, M. B., Michalak, I., & Detyna, J. (2019). Methods of extraction, physicochemical properties of alginates and their applications in biomedical field - a review. *Open Chemistry*, 17(1), 738–762. <https://doi.org/10.1515/chem-2019-0077>

Li, L., Zhu, B., Yao, Z., & Jiang, J. (2023). Directed preparation, structure–activity relationship and applications of alginate oligosaccharides with specific structures: A systematic review. *Food Research International*, 170, Article 112990. <https://doi.org/10.1016/j.foodres.2023.112990>

Lu, J.-W.; Zhu, Y.-L.; Guo, Z.-X.; Hu, P.; Yu, J. Electrospinning of sodium alginate with poly(ethylene oxide). *Polymer* **2006**, 47, 8026–8031.

Lucas N, Bienaime C, Belloy C, Queneudec M, Silvestre F, Nava-Saucedo JE (2008) Polymer biodegradation: mechanisms and estimation techniques. *Chemosphere* 73(4):429–442

M. Smith, D. C. Love, C. M. Rochman and R. A. Neff, *Curr. Environ. Health Rep.*, 2018, **5**, 375–386

Mahdiyah D, Mukti BH (2013) Isolation of polyethylene plastic-degrading bacteria. *Biosci Int* 2:29–32

Mahdiyah D, Mukti BH (2013) Isolation of polyethylene plastic-degrading bacteria. *Biosci Int* 2:29–32

Makarova, A. O., Derkach, S. R., Khair, T., Kazantseva, M. A., Zuev, Y. F., & Zueva, O. S. (2023). Ion-induced polysaccharide gelation: Peculiarities of alginate egg-box association with different divalent cations. *Polymers*, 15(5). <https://doi.org/10.3390/polym15051243>

- Meng K, Teng Y, Ren W, Wang B, Geissen V (2023) Degradation of commercial biodegradable plastics and temporal dynamics of associated bacterial communities in soils: a microcosm study. *Sci Total Environ* 865:161207
- Mortalò, C., Russo, P., Miorin, E., Zin, V., Paradisi, E., & Leonelli, C. (2023). Extruded composite films based on polylactic acid and sodium alginate. *Polymer*, 282, 126162.
- Nanda, N., & Bharadvaja, N. (2022). Algal bioplastics: current market trends and technical aspects. *Clean Technologies and Environmental Policy*, 24(9), 2659-2679.
- Nofal, R. M. (2022). Biodegradable textiles, recycling, and sustainability achievement. *Handbook of biodegradable materials*, 1-37.
- Okmoto K, Izawa M, Yanase H (2003) Isolation and application of a styrene degrading strain of *Pseudomonas putida* to biofiltration. *J Biosci Bioeng* 95(6):633–636.
- Pascoe, O. S. “Are Bioplastics the Solution to the Plastic Pollution Problem?” *PLOS Biology*, vol. 21, no. 3, Mar. 2023. <https://doi.org/10.1371/journal.pbio.3002045>.
- Pascoe, O. S. “Are Bioplastics the Solution to the Plastic Pollution Problem?” *PLOS Biology*, vol. 21, no. 3, Mar. 2023. <https://doi.org/10.1371/journal.pbio.3002045>.
- Pathak, V.M., Navneet, 2017. Review on the current status of polymer degradation: a microbial approach. *Bioresour Bioprocess* 4. <https://doi.org/10.1186/s40643-017-0145->

- Payanthoth, N. S., Mut, N. N. N., Samanta, P., Li, G., & Jung, J. (2024). A review of biodegradation and formation of biodegradable microplastics in soil and freshwater environments. *Applied Biological Chemistry*, 67(1), 110.
- Peteiro, C. Alginate production from marine macroalgae, with emphasis on kelp farming. In *Alginates and Their Biomedical Applications*; Rehm, B., Moradali, M., Eds.; Springer Series in Biomaterials Science and Engineering; Springer: Singapore, 2018; Volume 11
- Rashedy, S.H., Abd El Hafez, M.S.M., Dar, M.A., Cotas, J., Pereira, L., 2021. Evaluation and Characterization of Alginate Extracted from Brown Seaweed Collected in the Red Sea, vol. 11. *Applied Sciences*, Switzerland. <https://doi.org/10.3390/app11146290>.
- S. Lomartire, J.C. Marques, A.M.M. Gonçalves, An overview of the alternative use of seaweeds to produce safe and sustainable bio-packaging, *Appl. Sci.* 12 (2022) 3123, <https://doi.org/10.3390/app12063123>.
- S. Vardar, B. Demirel and T. T. Onay, *Rev. Environ. Sci. Bio/Technol.*, 2022, **21**, 205–223
- Saji, S., Hebden, A., Goswami, P., & Du, C. (2022). A brief review on the development of alginate extraction process and its sustainability. *Sustainability*, 14(9), 5181. <https://doi.org/10.3390/SU14095181>
- Siracusa V (2019) Microbial degradation of synthetic biopolymers waste. *Polymers (Basel)* 11(6):1066–1083
- Tosin M, Pishedda A, Degli-Innocenti F (2019) Biodegradation kinetics in soil of a multi-constituent biodegradable plastic. *Polym Degrad Stab* 166:213–218
- Trica, B.; Delattre, C.; Gros, F.; Ursu, A.V.; Dobre, T.; Djelveh, G.; Michaud, P.; Oancea, F. Extraction and Characterization of Alginate from an Edible Brown Seaweed (*Cystoseira barbata*) Harvested in the Romanian Black Sea. *Mar. Drugs* **2019**, *17*, 405
- United States Department of Agriculture—Agricultural Marketing Service. Alginates

Hadling/Processing. Available online: <https://www.ams.usda.gov/sites/default/files/media/Alginates%20TR%202015.pdf> (accessed on 19 June 2018)

- Urbanek AK, Rymowicz W, Mirończuk AM (2018) Degradation of plastics and plastic-degrading bacteria in cold marine habitats. *Appl Microbiol Biotechnol* 102(18):7669–7678
- Usov, A. I., & Zelinsky, N. D. (2013). Chemical structures of algal polysaccharides. *Functional Ingredients from Algae for Foods and Nutraceuticals*, 23–86. <https://doi.org/10.1533/9780857098689.1.23>
- V. Bátori, D. Åkesson, A. Zamani, M. J. Taherzadeh and I. Sárvári Horváth, *Waste Manage.*, 2018, **80**, 406–413
- Williams, P.A.; Phillips, G.O. Introduction to Food Hydrocolloids. In *Handbook of Hydrocolloids*; Woodhead Publishing: Sawston, UK, 2021; pp. 3–26
- Yoo, S.; Krochta, J.M. Whey protein–polysaccharide blended edible film formation and barrier, tensile, thermal and transparency properties. *J. Sci. Food Agric.* **2011**, *91*, 2628–2636
- Younes, M.; Aggett, P.; Aguilar, F.; Crebelli, R.; Filipič, M.; Jose Frutos, M.; Galtier, P.; Gott, D.; Gundert-Remy, U.; Georg Kuhnle, G.; et al. Re-evaluation of alginic acid and its sodium, potassium, ammonium and calcium salts (e 400–e 404) as food additives. *EFSA J.* **2017**, *15*, 5049.
- Zanchetta, E., Damergi, E., Patel, B., Borgmeyer, T., Pick, H., Pulgarin, A., et al. (2021). Algal cellulose, production and potential use in plastics: Challenges and opportunities. *Algal Res.* **56**, 102288. doi: 10.1016/j.algal.2021.102288
- Zhou J, Gui H, Banfield CC, Wen Y, Zang H, Dippold MA, Charlton A, Jones DL (2021) The microplastisphere: biodegradable microplastics addition alters soil microbial community

structure and function. Soil Biol Biochem 156:108211