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From Bio-Plastics to Sustainable Plastics: The Emerging Role of Seaweeds

Inderdeep Kaur and Anjana Sagar*
Department of Botany, Sri Guru Tegh Bahadur Khalsa College,
University of Delhi, Delhi 110 007, India
*Email: anjana@sgtbkhalsa.du.ac.in

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Abstract

The petro-based plastics which were lauded during past for having facilitated globalization, are now being condemned for generating a large environment-footprint. As the plastic menace takes huge dimensions in the landfills and open areas, the convenience of urban way of living continues to drive its market. Keeping in view the plastic pollution, the Sustainable Development Goals (SDGs) also resonate the need for safe plastic waste handling. Out of 17 goals mentioned in Agenda for Sustainable development, 12 goals are impacted by plastic handling in either the direct or indirect way. To reduce the plastic trash, an environment-friendly alternative may be through the 'bio-plastics'. These plastics are obtained from biodegradable and renewable biological sources. Bio-plastics therefore, have a smaller e-footprint and work well with waste handling set ups to promote green eco-friendly disposal. However, their biodegradation is not free of emissions. They generate Green House Gases (GHGs) or emissions during End of Life (EoL) processes such as landfilling. The biogenic carbon which is released from the bio-based, biodegradable plastics adds to the complexity of bio-plastics. The new innovations and policies focus on source of plastic and its end of life. The present review focuses on the novel option in bio-plastics – seaweed-based bio-plastics. Seaweed resource has potential as a sustainable alternative to bio-plastics due to its low water footprint and land footprint. Besides, the novel polysaccharides such as alginates and carrageenans in the biomass have a huge potential in replacing packaging material. It also brings forth the need to work on strengthening the seaweed plastic for more durability and functionality. Attention is also drawn to innovating green disposal strategies and need for policies to beat plastic pollution.

1. Introduction

Plastics have not only revolutionized industries, but have also improved quality of our lives and helped make technological progress happen (Andrady and Neal, 2009; North and Halden, 2013). The helpfulness, durability and cost-effectiveness of plastics make them essential in various utilization practices, putting them at the forefront. Plastics have become an integral part of the industry - from solar panels to turbines, from healthcare (medical grade plastics) to aerospace

(Carbon-fiber-reinforced plastics), the industries cannot do without it (Geyer *et al*., 2017). The automotive interiors resistant to UV degradation have reshaped the world around us. The plastics are made of carbon molecules obtained from either oil refining raw material or gas extraction processes. Ethylene, the most abundantly produced hydrocarbon is the precursor for synthetic petroleum-based polyethylene (PE), polyethylene terephthalate (PET), polyesters, polyvinyl chloride (PVC), and polystyrene (PS). After use, this plastic is discarded ending up in landfills or takes the shape of unregulated waste. The plastic trash heap *then* not only chokes the environment, but also contaminates our food supply, and drives climate change. The problem lies not in PE, polypropylene (PP), and PVC but the plastic as a product which is non-biodegradable, is fossil-fuel based, is unsustainable and is rampantly used (Fig 1).

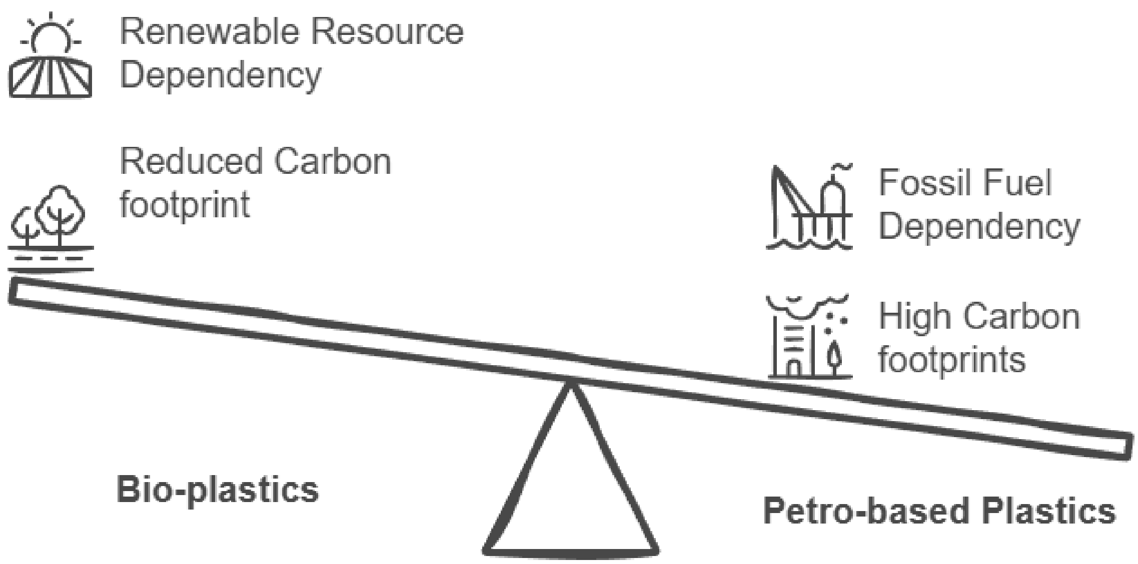

Figure 1. Bio-plastics, a sustainable alternative to synthetic petro-based plastics.

Once discarded in the landfills, plastic waste can release obnoxious gases that are released into the environment adversely impacting the wildlife. The steam-cracking process through which plastics are made, requires high energy and heat. This is provided by burning of fossil-fuel making plastics inextricably tied to carbon emissions responsible for climate change. In its worst form, the single use plastic emits huge amounts of GHGs. The slow degradation of plastics, combined with the GHGs emitted by plastic from the landfills has resulted in a significant carbon footprint. In marine and terrestrial ecosystems, the accumulation of plastic waste is killing biodiversity (Blair and Mataraarachchi, 2021; Vadera and Khan, 2021). The macro-plastics (> 5 mm) and micro-plastics (< 5 mm) in the waste (Moore, 2008), not only contaminate our ecosystems, but are a source of toxic pollutants into the food chain. When biomagnified these plastics ultimately threaten human health (Thompson *et al.*, 2009; Vadera and Khan, 2021). As the planet continues to fight the mounting crisis of petroleum-based (or petro-based) plastic pollution, the scientists and innovators are turning to nature for sustainable alternatives. The mankind has pinned up hopes on bio-plastics. Many plants such as maize, potato, oils from vegetables, wood, food waste, cereal crops, have yielded bio-plastics. These alternatives to plastics are starched-based and are part of 'green chemistry'. Some of the common bio-plastics are: (PLA), poly-3-hydroxybutyrate

(PHB), polyamide (PA), and organic polyethylene (PE) (Burelo *et al.*, 2023). The biggest limitation of the biodegradable bio-plastic is that it is not sustainable. The review is written in the backdrop of 17 SDGs, with at least 12 impacted by plastic issues (Walker, 2021). As defined by Gonella and de Gooyert (2024), sustainable plastics comprise plastic materials that are put into production of products which not only provide societal benefits but also enhance human and environmental health, and safety across the entire product life cycle. It discusses the limitations of bio-plastics and emphasizes the need for innovation *in sustainable bio-plastics*. It also offers seaweed resources as potential and sustainable candidates ready to revolutionize the plastic industry.

2. Environmental Footprint of Plastic

The Second World War in 1940 witnessed plastic being put to commercial use. Since then, the picture has become petrifying. The single-use plastic may account for 5-10% of all GHG emissions by the year 2050. When disposed as trash, there are three basic problems with unattended plastic as a material. First, is that being non- biodegradable it can stay on earth for even centuries. Second, is its capacity to generate micro- and nano- plastics that enter food chains in both aquatic and terrestrial ecosystems. And third, since it is made from petroleum-based feedstock, it leaves a huge carbon footprint, contributing to global warming. This is because exposure to ultraviolet radiation, brings photo-oxidation of the discarded plastic, causing it to become brittle (Gunawardhana *et al*., 2023). The fragmented plastic circulates in different environments affecting several species of plants and animals due to its toxic impacts. The plastic manufacturing involves a wide range of chemicals. There may be additives like fillers, plasticizers, pigments, foaming agents, processing aids, lubricants, and heat stabilizers used by plastic industry. Besides these, acid scavengers, anti-oxidants, UV stabilizers, flame retardants, and some antistatic agents are also used. All these chemicals and agents in different quantities control properties of plastic such as increased durability, enhanced performance, and appearance (Pilapitiya and Ratnayake, 2024). As we enjoy life that cannot be imagined without plastic, it is important to delve over our reliance on this material. There seem to be three basic reasons: (i) plastic easily replaces traditional materials such as ceramic, wood, and glass because of its durability (Andrady and Neal, 2009), (ii) population has increased sharply during the past years swelling the consumers who are pro-plastic (Pilapitiya and Ratnayake, 2024), and (iii) easy access in the market which readily accepted it as a practical material in packaging and fields such as medicine (Kedzierski *et al*., 2020).

Plastic in the environment has been observed to be ingested by marine, terrestrial and freshwater species. Plastic leads to nutritional dilutions, limited mobility, strangulation, habitat displacement, and toxicity to the wild life. Plastic ingested or otherwise leads to decreased reproduction or even mortality in a population. This loss can have far reaching effects and can impact the entire food web and biodiversity. Plastic breaks down generates micro-plastics, nano-plastics, and polymer-associated chemicals. Micro-plastics have been detected in the human gut, lung tissues, blood, and placental tissues (Jenna and Walker-Franklin, 2023). Micro-plastics have generated widespread attention within research and the media. They can travel far off through the environment and also locally within organisms, animals, and the human body. Small-sized polystyrene from plastics reduces the number and size of egg cells, affects sperm motility, and larval number for oysters (Sussarellu *et al*., 2016). Nano-plastics smaller than 1 μm, are known to travel a great distance in the environment and enter biological tissues directly impacting humans via inhalation, ingestion, and skin exposure to plastic particles. Plastics can also get entangled around the feet, wings or bodies of the animals. Entanglement causes suffocation, drowning, strangulation, with an inability to escape from predators due to diminished mobility, migration activities, and may finally lead to death. Another implication of the plastic menace is transport of invasive species. Vectors of invasive species drafting through plastic debris along with the resilience, and buoyancy of plastics create long-range transport of species/materials to far off ecosystems (Andrade *et al.*, 2021). Corals are known to often consume micro-plastics which are mistaken as zooplankton due to their size similarities (John *et al*., 2021).

3. Bio-plastic- The 'Good' Plastic

Bio-plastics comprises materials that can be 1) bio-based (also known as "drop-in-polymers", 2) compostable/biodegradable and 3) materials that are not bio-based or are simply, a combination of both properties (Rosenboom *et al*., 2022). The 'drop-in-polymers' are exemplified as bio-polyethylene [bioPE], and bio-polyethylene terephthalate [bioPET]). The biodegradable but not bio-based are polybutylene adipate-co-terephthalate [PBAT], polycaprolactone [PCL] while polyhydroxyalkanoates [PHAs], polylactic acid [PLA], polybutylene succinate [PBS], and starch-based polymers are a mix of 1) and 2). According to European Bioplastics (2022), the most widespread and promising types are PLA, PHA and starch blends (Fig. 2).

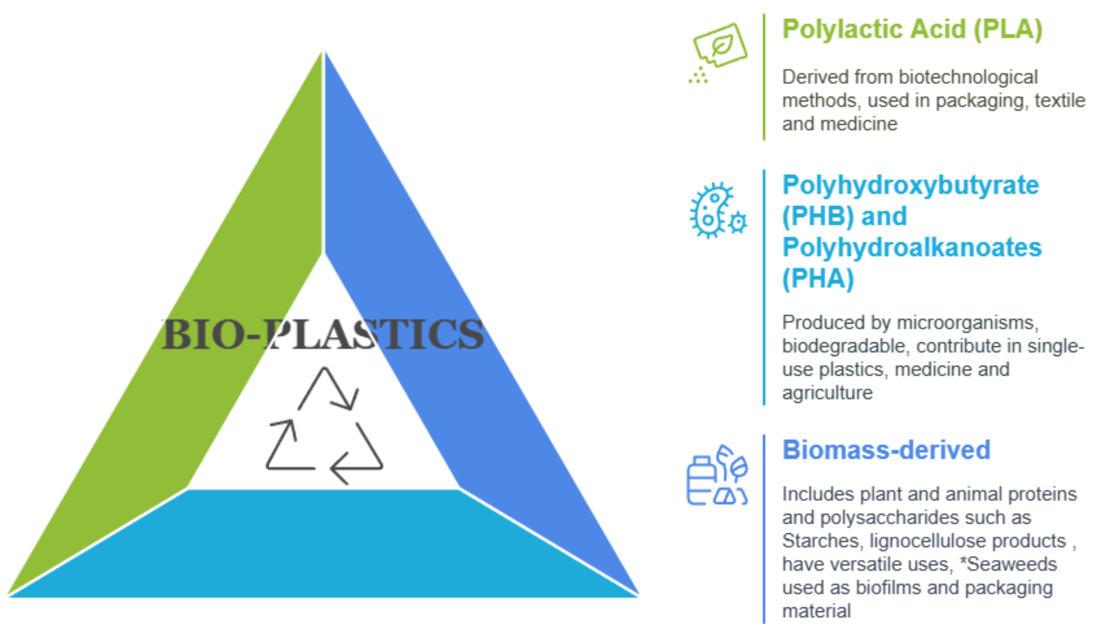

Figure 2. Bio-plastics: sources and utilization

Polylactic Acid is a polyester made from fermented plant starch of Zea, cassava, sugarcane or sugar beet pulp. Lactic acid, a by-product of fermentation is chemically polymerized to yield PLA. Conversely, Polyhydroxybutyrate (PHB) is a polyhydroxyalkanoate (PHA), a polymer belonging to the class polyesters. PHB is produced by microbes (such as *Cupriavidus necator*, *Methylobacterium rhodesianum* or *Bacillus megaterium*) growing under physiological stress and limited nutrient availability such as nitrogen or phosphorous. These compounds are accumulated as granules coated by proteins such as polymerases, depolymerases and phasins (Prieto *et al*., 2016). Polyethylene (PE) is a combination of more than 500 ethylene subunits while Polyglycolic acid (PGA), a linear aliphatic polyester is synthesized by polymerization reaction of ring-opening of cyclic glycolide monomers (Zhang *et al.,* 2017) (Fig. 3). The advantages of deploying renewable bio-based solutions for synthetic plastics are indisputable. However, before applauding the benefits of bio-plastics it is important to investigate End-of-Life (EoL) concept, and their impact on human health and the environment. This concept is still subject to discussion due to more than one reasons. Once bio-plastics are disposed in the open environment (e.g. soil, estuaries, oceans), their structure and biodegradability are factors controlled by the surrounding biotic (animals) and abiotic factors (e.g. sunlight, oxygen, pH, temperature, moisture). The breakdown of polymer chains may occur but complete mineralization may not happen. They may also generate micro-bio-plastics and nano-bio-plastics (Cucina *et al*., 2021). Though these bio-plastics are 'temporary' in the open environment, but the broken-down pieces can easily migrate and act as vectors. In transit they interact with metals and persistent organic pollutants. As a result both are transported together to other locations (Miri *et al*., 2022). Micro(bio)plastics might also disrupt soil and aquatic biota by changing the physicochemical properties of ecosystems (Ali *et al.,* 2023). Currently, only 'drop-in polymers' are included in the existing recycling streams; the remaining bio-plastics are treated as contaminants of conventional plastics (Pereyra-Camacho and Pardo, 2024). When bio-plastics are mixed with conventional plastics, various sorting technologies (e.g., gravity and triboelectric-based sorting) are required for their disposal (Serrano-Aguirre *et al*., 2024).

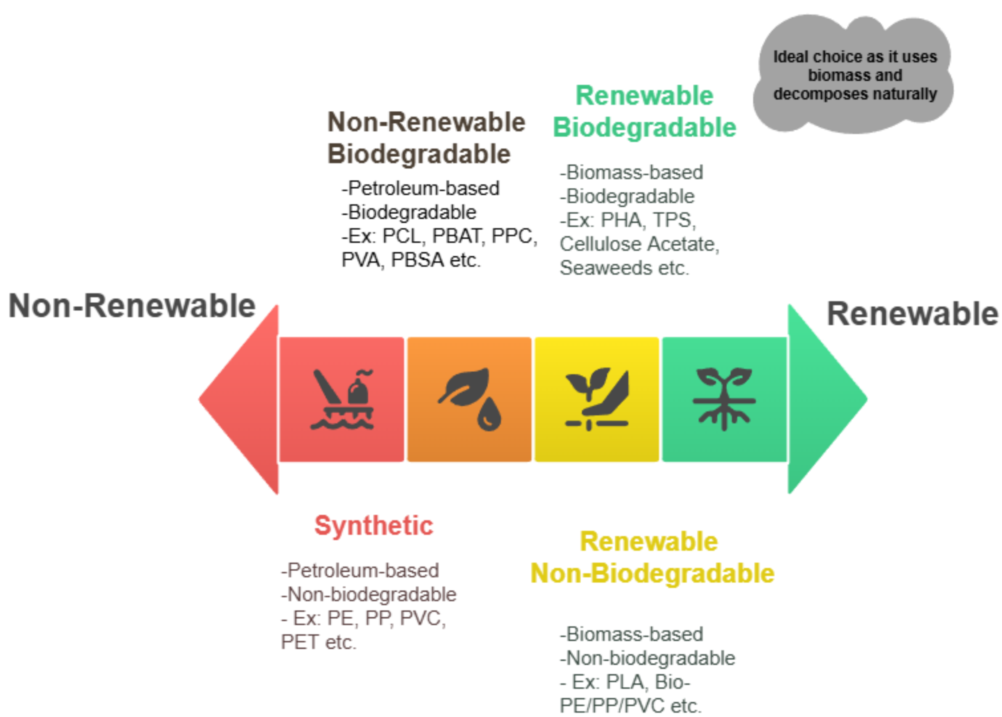

Figure 3. Diagrammatic representation to understand plastic types based on renewability and biodegradability.

Presently among the various applications for bio-plastics, packaging, mulching and disposable products (short to medium life span) are the most popular applications (Box 1). Bio-plastic use is expected to grow in the textile industry, agriculture, sport fishing, hunting, horticulture and electronics (European Bioplastics, 2022). The key challenges in bio-plastic adoption and production include competition with food production for feedstock, high production costs, and uncertainty in end-of-life management (EoL). They have limited biodegradability, lack standardization, and have technical performance limitations. Moreover, they require management and production to maximize their environmental benefits. However, owing to insufficient ecotoxicological data, and the technology for assessment, current status on environmental issues of bio-plastics remains unexplored (Woods *et al*., 2021). The major hindrance to implementation of bio-plastics is the effective downstream recycling which must be worked out since the market of bio-plastics has increased.

4. Time for the 'Sustainable' plastic

Bio-based plastics are made from raw materials that are otherwise used as food. The arable land on which, for example, corn and sugar cane are grown for bio-plastics cannot be put under crop cultivation. Meeting the food demand for the global population is tough if arable land is used for packaging material. Chen *et al*. (2024) estimated that bio-based plastics such as Polybutylene adipate-co-terephthalate blended with Polylactide (PBAT- LA/PLA) emit 13.53–62.19% lower carbon emissions equivalent of per kilogram than traditional plastics in China, depending on feedstock and manufacturing methods. Bio-plastics with a carbon footprint lesser than petro-based plastics are therefore not a complete sustainable option due to competition with food crops, fertilizer use, and land/water demands (Balamurugan *et al*., 2024). The industry continues to find alternatives with lesser land and water demands, and a lesser environment footprint. One such promising solution to bio-plastics is a group of macro- marine algae popularly known as seaweed (Lomartire *et al*., 2022). The seaweeds with emerging applications as bio-plastics have the potential to revolutionize the packaging industry. The potential of seaweed-based bio-plastic lies in the polysaccharides present in the biomass and biodegradability and renewability of the 'plastic' (Zanchetta *et al*., 2021). Besides, they are fast-growing (at about 30-60 times) than land-based plants and produce high biomass (Sharma *et al*., 2025).

The novel polysaccharides namely alginates and carrageenans in seaweed tissues have a polymer structure, which gives the material stretchability, flexibility, and transparency. The high natural polymer content allows it to be molded into various packaging forms, from films to pouches, while maintaining its durability (Santana *et al*., 2024). The carrageenans can be mixed with *Sorghum* starch in 30:70 (%v/v) to improve tensile strength. Like-wise various starch ratios (with potato starch, mango pulp) can generate desired films from seaweeds. Most importantly, the material is appreciated for the ability of the product to go back to the planet much more easily than other bio-plastics. Seaweed-based packaging decomposes within weeks (Box 1) and is therefore not a pollutant. Bio-plastics have been produced from brown algae such as *Laminaria japonica, Padina pavonica,Sargassum wightii*, and *Sargassum natans*, red algae such as *Kappaphycus* and *Gracilaria* and green algae such as *Ulva* (Doh *et al*., 2020; Dalal *et al*., 2023; Khan *et al*., 2024; Khan *et al*., 2025).

BOX 1-The rise of good plastic

- Globally, more than 50 billion plastic water bottles are thrown out each year while US alone throws 1500 water bottles per second!
- First bio-plastic PHB was made by Maurice Lemoigne in 1926 from bacterial feedstock.
- In 2014, engineering students Rodrigo García González, Pierre-Yves Paslier and Guillaume Couche developed an idea of seaweed-based bio-plastic, introducing as a prototype of an edible bottle.
- Notpla has innovated novel seaweed-based liquid packaging product, Ooho. It is an encapsulated liquid in a thin flexi-layer and is biodegradable. One can even pop the water pod!
- Ooho was offered as thirst quencher in marathon to runners during London marathon, Bari Half, Vitality Half Marathon.
- Seaweed bio-plastic can also be used in food packaging as a waterproof and greaseproof coating on cardboard (Nešić *et al*., 2024; Jaffar *et al*., 2025).
- Meanwhile, experimental design studios such as Agar Plasticity and Icelandic designer Ari Jónsson are exploring and experimenting with seaweed bio-plastics.
- Evoware under their flagship line, Ello Jello, in 2016 launched edible seaweed cups in various flavors from orange to green tea to address the Jakarta plastic waste crisis. The company also produces edible food wrapping and single use sachets, typically used for instant coffee or food condiments. Zerocircle, and Sea6Energy are Indian innovations for seaweed bio-plastic films, straws, cups and packaging material (Pandey, 2023).

To achieve enhanced mechanical properties of bio-plastics, crude extracts are commonly mixed with a plasticizer such as glycerol (Torrejon *et al*., 2025). However, utilization of pure alginate or carrageenan as primary ingredients for bio-plastics poses some restrictions. This is because they readily allow water vapor to pass through and lack of water resistance (Kontominas, 2020). These limitations can be overcome by blending alginates with starches. The use of glycerol creates bio-plastic films those are less permeable to gases and with improved strength and flexibility (Khalil *et al.,* 2017). The other option is to add nano-particles or clays which extend the shelf life of a variety of products. Studies have shown that alginate-based films are shown to protect meat products by minimizing moisture loss or color fading or microbial growth or gas transfer. To tackle the problem of plastic waste, Indonesia uses it in making edible cups and food wrappers, among other items, (Box 1).

However, seaweed bio-plastics may not be a good option where bending and stretching is the critical requirement. The future development of bio-plastics could focus on improving elongation at break while preserving overall mechanical integrity. Dried alginate gels have been suggested for novel bio-plastic products as these gels can be easily stored and subsequently rehydrated. Additionally, the seaweeds contain phenols which are anti-bacterial and anti-fungal. Hence any food packaging material of seaweed base should have similar properties and might prevent the foodborne pathogens (Lomartire and Gonçalves, 2024). Such properties of the biofilms await scientific attestation. Also, the seaweed-based products are not at present cost-effective. However, if the market requirement for these products increases in future then this could drive down the production cost.

5. Mariculture- is Plastic on the Seaweed?

Seaweed farming, to obtain bulk biomass, carried out in the ocean is a practice in all coastal areas around the globe. This solves the issues of over-exploitation of renewable resources, the seaweeds allowing the multi-billion dollars seaweed industry to run. Unlike land plants, seaweeds regenerate faster and are not under threat if commercialization is permitted but also regulated by stringent government policies (Sharma *et al.*, 2025).

The petro-based plastic on the beach can affect seaweed farming in two ways. In one possibility, the micro-plastics generated from discarded plastic by people visiting the shores might deteriorate seaweed quality. Though seaweeds do not consume 'food' as such and therefore, 'seemingly' face no danger from micro-plastics entering the system. Still, the authentic tests on biomass need to be done before the tissues are accepted as plastic-free. Investigations on *Fucus vesiculosus* and several red algae such as *Chondrus crispus*, *Grateloupia turuturu* reveal that the alga retains suspended micro-plastics on its surface (Gutow*et al*., 2015; Jung *et al.,* 2023). Li *et al*. (2022) identified five accumulation mechanisms in macro-algae, namely wrapping, attachment, embedment, entanglement and entrapment.

Research on *Saccharina japonica* and *Pyropia yezoensis* (nori) revealed widespread contamination and spread of micro-plastics by dietary seaweeds in East Asia (Xiao *et al*., 2024). The other aspect is related to seaweed cultivation practices. Farmers use plastic bottles to keep the rafts with seaweed sporelings afloat. The hook is also synthetic plastic adding to the increased surface available for micro-plastic adsorption. Marine organisms that live on the ropes and lines used for seaweed farming are also affected. About 90% of the organisms on the main ropes and 75% on the longlines were reported to accumulate micro-plastics, averaging 0.29 and 0.14 pieces/g, respectively. Even the organisms living on floating bottles showed a 77% contamination rate (Werorilangi *et al.,* 2023).

6. Time to Ponder

Plastic is integrated into almost all activities of our lives and has somewhat become inseparable. But one need to understand the environmental, social, economic and health risks plastics bring along. It is equally important to understand the implications of single use plastic on ecosystem health and its role in climate change. While global efforts include a Global Treaty to end plastic pollution (Box 2), the most impactful step would be an initiative at individual level.

By changing our behavior and life style, we can together fight plastic menace. We should be more watchful of the brands that use petro-based plastics, and single use plastic bags. Visiting restaurants that allow one to get plastic-free containers is a step to beat plastic pollution. Gaining insight into ways to reduce plastic footprint should be encouraged through educational institutes. Let the young minds be trained towards plastic-free campus. This is bare minimum one can do for a better tomorrow.

BOX 2 - The field of bio-plastics is wide open amidst policies to fight plastic menace

- Seaweed can be processed to make bio-plastic which is not only biodegradable but safe to consume also. This alternative could displace conventional single use plastic that accounts as primary pollutant for marine ecosystem.
- At present Japan, European nations and other countries are leading in the plastic waste treatment technology and are developing environmentally sustainable plastics alternatives.
- Cambodia has moved to protect its environment from plastic bag waste by addressing all stages, namely import, production, distribution, and consumption in 2017.
- Malaysia government implemented a ban on the importation of plastic waste in 2017. Other countries with a ban on plastics are - India (2002), Bangladesh (2002), Rwanda (2004), Eritrea (2005), Somaliland (2005), Tanzania (2006), Republic of Congo (2011), Niger (2013), Cameroon (2014), Ivory Coast (2014), Gambia (2015), Madagascar (2015), Senegal (2015), Malawi (2015), Papua New Guinea (2016), Morocco (2016), France (2016), Nepal (2016), Georgia (2017), Moldova (2017), Benin (2017), Tunisia (2017), Panama (2018), Australia (2018), Turkey (2019), Bahamas (2020), and Ethiopia (2020) .
- South Korea practices a model system popularly known as 'pay-as-you-throw' to control plastic waste at its EoL stage (Murti *et al*., 2022).
- Taxation stands out as an exemplary solution to control plastic pollution. The plastic tax shares conceptual similarities with the carbon tax and is considered a part of green taxation (Norouzi *et al*., 2022; Desalegn and Tangl, 2022; Abate and Elofsson, 2024; WTS Global, 2024). This taxation imposed in several European countries aims to reduce plastic consumption by raising the cost of the product through taxes. Countries implementing tax are - Germany (1991), Denmark (1994), Ireland (2002), South Africa (2003), Romania (2006), Macedonia (2009), Gabon (2010), Hong Kong (2015), Portugal (2015), Mozambique (2016), Netherlands (2016), Israel (2017), Estonia (2017), Norway (2017), Colombia (2017), Cyprus (2018), Czech Republic (2018), Poland (2018), Greece (2018), Lithuania (2018), Luxemburg (2018), Spain (2018), Croatia (2019), and Latvia (2019).
- The 'plastic waste trade' was introduced as a solution to address the uncontrollable growth of plastic waste in Europe. It is now accepted as a global business dedicated to treatment, disposal, and/or recycling of plastic waste (Zhao *et al*., 2021).
- The amended Basel Convention (2021) regulates transboundary plastic waste trade and over 100 countries implemented item-specific bans (e.g., EU/India on bags/straws), no binding global framework restricts plastic production at source.
- In 2022, UN Member States adopted a historical resolution to create an Intergovernmental Negotiating Committee (INC-1) in order to develop a worldwide convention to end land and marine plastic pollution.
- The UN Environment Assembly (UNEA-5), culminated in the UN Global Plastics Treaty (finalized in April 2024), which targets 2040 for elimination through single-use plastic restrictions and production limits (UNEP, 2024).
- Furthermore, it is critical at this stage to strengthen cooperation in education so that green and sustainable consumption practices can be instilled in the public.

7. Conclusion

The change in the mindset of consumers has to occur if petro-based plastic is to be eliminated. Seaweeds have offered biomass, bioactive substances and formulations to various industries with a high success rate. It is therefore, not doubtful if we bet on sustainability from seaweed-based-bio-plastics. However, the ecological constraints posed by the habitat are rendering seaweeds unfit especially in food and drug industry. In case of bio-plastics, the limitations are posed in addition, by high production cost, low demand, and lesser durability and limited application. Seaweed is nothing short of miracles but these humble plants have some basic requirements. It should be considered that seaweed grows on 70% of earth's surface. Furthermore, it is in no conflict with other species for space and needs no extra resources, and then it is our responsibility to allow it a safe 'niche'. If the problems of ocean pollution are addressed, perhaps seaweed can be part of the plastic solution. Even though, farming of seaweeds is simple and done in vast oceans, yet each ecosystem has a carrying capacity and the water resources cannot be continued to be mindlessly exploited. The farming techniques should also follow good practices protocol along with efficient coordination of seaweed supply chains. A major challenge is of developing alternative and targeted waste management solutions for the oceans, as the disposable plastic garbage continues into ever growing mound.

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References

Abate, T.G.., Elofsson, K., 2024. Environmental taxation of plastic bags and substitutes: Balancing marine pollution and climate change. *Journal of Environmental Management,* 359, 120868. https://doi.org/10.1016/j.jenvman.2024.120868

Abdul Khalil, H.P.S., Saurabh, C.K.., Tye, Y.Y.., Lai, T.K.., Easa, A.M.., Rosamah, E., Fazita, M.R.N., Syakir, M.I., Adnan, A.S., Fizree, H.M., Aprilia, N.A.S., Banerjee, A., 2017. Seaweed based sustainable films and composites for food and pharmaceutical applications: A review. *Renewable and Sustainable Energy Reviews,* 77, 353–362. https://doi.org/10.1016/j.rser.2017.04.025

Ali, S.S., Abdelkarim, E.A., Elsamahy, T., Al-Tohamy, R., Li, F., Kornaros, M., Zuorro, A., Zhu, D., Sun, J., 2023. Bioplastic production in terms of life cycle assessment: A state-of-the-art review. *Environmental Science and Ecotechnology,* 15, 100254. https://doi.org/10.1016/j.ese.2023.100254

Andrade, H., Glüge, J., Herzke, D., Ashta N.M., Nayagar, S.M., Scheringer, M., 2021. Oceanic long-range transport of organic additive presents in plastic products: An overview. *Environmental Sciences Europe,* 33, 85. https://doi.org/10.1186/s12302-021-00522-x

Andrady A.L., Neal, M.A., 2009. Applications and societal benefits of plastics. *Philosophical Transactions of the Royal Society London B Biological Sciences,* 364, 1977-1984. https://doi.org/10.1098/rstb.2008.0304

Australia-Indonesia Centre 2023. *End-of-life of plastics used in seaweed aquaculture in South Sulawesi*. Online from https://pair.australiaindonesiacentre.org/wp-content/uploads/2024/01/PAIR_End-of-life-of-plastics-used-in-seaweed-aquaculture-in-South-Sulawesi.pdf

Balamurugan, A., Nath, J., Rao, H.G., Venkata, V., Nori, S.S., Suryanarayan, S., 2024. *Seaweed derived sustainable packaging*, pp. 263–287. In: Hefft, DI., Adetunji, CO. (eds.), Applications of Seaweeds in Food and Nutrition, Elsevier, New York.

Basel Convention, 2021. *Plastic waste amendments*. Online at: https://www.basel.int/Implementation/Plasticwaste/Amendments/Overview/tabid/8426/Default.aspx

Blair, J., Mataraarachchi, S., 2021. A review of landfills, waste and the nearly forgotten nexus with climate change. *Environments,* 8(8), 73. https://doi.org/10.3390/environments8080073

Burelo, M., Hernández-Varela, J.D., Medina, D.I., Treviño-Quintanilla, C.D., 2023. Recent developments in bio-based polyethylene: Degradation studies, waste management and recycling. *Heliyon,* 9(11), e21374. https://doi.org/10.1016/j.heliyon.2023.e21374

Chen, G., Li, J., Sun, Y., Wang, Z., Leeke, G.A., Moretti, C., Cheng, Z., Wang, Y., Li, N., Mu, L., Li, J., Tao, J., Yan, B., Hou, L., 2024. Replacing traditional plastics with biodegradable plastics: Impact on carbon emissions. *Engineering,* 32, 152–162. https://doi.org/10.1016/j.eng.2023.10.002

Cucina, M., de Nisi, P., Tambone, F., Adani, F., 2021. The role of waste management in reducing bioplastics' leakage into the environment: A review. *Bioresource Technology,* 337, 125459. https://doi.org/10.1016/j.biortech.2021.125459

Dalal, S.R., El-Naggar, N.E-A., El Naeem, G,A,E., 2023. Biosynthesis of sustainable biodegradable bioplastics using alginate extracted from *Padina pavonica*, optimization and characterization. *Algal Research,* 76, 103325. https://doi.org/10.1016/j.algal.2023.103325

Desalegn, G., Tangl, A., 2022. Banning vs taxing: Reviewing the potential opportunities and challenges of plastic products. *Sustainability,* 14(12), 7189. https://doi.org/10.3390/su14127189

Doh, H., Dunno, K.D., Whiteside, W.S., 2020. Preparation of novel seaweed nanocomposite film from brown seaweeds *Laminaria japonica* and *Sargassum natans*. *Food Hydrocolloids,* 105, 105744. https://doi.org/10.1016/j.foodhyd.2020.105744

European Bioplastics, 2022. *What are bioplastics?* Online at: https://docs.european-bioplastics.org/publications/fs/EuBP_FS_What_are_bioplastics.pdf

Geyer, R., Jambeck, J.R., Law, K.L., 2017. Production, use, and fate of all plastics ever made. *Science Advances,* 3, e1700782. https://doi.org/10.1126/sciadv.1700782

Gonella, S., de Gooyert, V., 2024. What are sustainable plastics? A review of interrelated problems and solutions to help avoid unintended
consequences. *Environmental Research Letters*, 19(7), 073001. https://doi.org/10.1088/1748-9326/ad536d

Gunawardhana, G.M.S.S., Perera, U.L.H.P., Ratnayake, A.S., 2023. Sources and fate of plastics into microplastics degradation and remediation methods. pp. 155–170. In: Vithanage, M., A. de Alwis, A.P., Botheju, D., (eds.), *Maritime Accidents and Environmental Pollution—the X-Press Pearl Disaster: Causes, Consequences, and Lessons Learned*, vol.1, CRC Press, Boca Raton. https://doi.org/10.1201/9781003314301-8

Gutow, L., Eckerlebe, A., Gimenez, L., Saborowski, R., 2015. Experimental evaluation of seaweeds as a vector for microplastics into marine food webs. *Environmental Science and Technology* 50(2), 915–923. https://doi.org/10.1021/acs.est.5b02431

Jaffar, S.S., Saallah, S., Misson, M., Siddiquee, S., Roslan, J., Lenggoro, W., 2025. Development and characterization of carrageenan/nanocellulose/silver nanoparticles bionanocomposite film from *Kappaphycus alvarezii* seaweed for food packaging. *International Journal of Biological Macromolecules,* 311, 143922. https://doi.org/10.1016/j.ijbiomac.2025.143922

Jambeck, J.R., Walker-Franklin, I., 2023. The impacts of plastics' life cycle. *One Earth,* 6(6), 600–606. https://doi.org/10.1016/j.oneear.2023.05.015

John, J., Nandhini, AR., Chellam, PV., Sillanpää, M., 2022. Microplastics in mangroves and coral reef ecosystems: A review. *Environmental Chemistry Letters,* 20(1), 397–416. https://doi.org/10.1007/s10311-021-01326-4

Jung, J.W., Xing, Q., Park, J.S., Kim, Y.J., Yarish, C., Kim, J.K., 2023. Physiological effects of micro-plastics on the red algae, *Grateloupia turuturu* and *Chondrus* sp. *Aquatic Toxicology,* 261, 106609. https://doi.org/10.1016/j.aquatox.2023.106609

Kedzierski, M., Lechat, B., Sire, O., Le Maguer, G., Le Tilly, V., Bruzaud, S., 2020. Microplastic contamination of packaged meat: Occurrence and associated risks. *Food Packaging and Shelf Life,* 24, 100489. https://doi.org/10.1016/j.fpsl.2020.100489

Khan, N., Sudhakar, K., Mamat, R., 2025. Biodegradable plastics from marine biomass: A solution to marine plastic pollution. *Journal of Hazardous Materials Advances,* 17, 100559. https://doi.org/10.1016/j.hazadv.2024.100559

Khan, N.M., Chakma, P., Uddin, M., Hasan, C.Md.M., 2024. Preparation and characterization of biodegradable plastic from red seaweed (*Gracilaria* sp.) from coastal areas in Bangladesh. *Chemistry Select,* 9 (34), e202401990. https://doi.org/10.1002/slct.202401990

Kontominas, M.G., 2020. Use of alginates as food packaging materials. *Foods,* 9(10), 1440. https://doi.org/10.3390/foods9101440

Li, Q., Su, L., Ma, C., Feng, Z., Shi, H., 2022. Plastic debris in coastal macroalgae. *Environmental Research, 205*, 112464. https://doi.org/10.1016/j.envres.2021.112464

Lomartire, S., Gonçalves, A.M.M., 2024. Seaweed-based biodegradable packaging: A green alternative for a plastic-free future. pp. 271–295. In: Bala, K., Ghosh, T., Kumar, V., Sangwan, P., (eds), *Harnessing Microbial Potential for Multifarious Applications. Energy, Environment, and Sustainability*. Springer, Singapore. https://doi.org/10.1007/978-981-97-1152-9_11

Lomartire, S., Marques, JC., Gonçalves, AMM., 2022. An overview of the alternative use of seaweeds to produce safe and sustainable bio-packaging. *Applied Sciences,* 12(6), 3123. https://doi.org/10.3390/app12063123

Miri, S., Saini, R., Davoodi, SM., Pulicharla, R., Brar, S.K., Magdouli, S., 2022. Biodegradation of microplastics: Better late than never. *Chemosphere,* 286, 131670. https://doi.org/10.1016/j.chemosphere.2021.131670

Moore, C.J., 2008. Synthetic polymers in the marine environment: A rapidly increasing, long-term threat. *Environmental Research, 108*(2), 131- 139. https://doi.org/10.1016/j.envres.2008.07.025

Murti, Z., Dharmawan, Siswanto, Soedjati, D., Barkah, A., Rahardjo, P., 2022. Review of the circular economy of plastic waste in various countries and potential applications in Indonesia. In: *Proceedings of 4th International Conference on Environment, Sustainability Issues, and Community Development (INCRID), Semarang, Indonesia*, 1098(1), 012014. IOP Publishing, Bristol, UK. https://doi.org/10.1088/1755-1315/1098/1/012014

Nešić, A., Meseldzija, S., Benavides, S., Figueroa, F., Cabrera-Barjas, G., 2024. Seaweed as a valuable and sustainable resource for food packaging materials. *Foods,* 13, 3212. https://doi.org/10.3390/foods13193212

Norouzi, N., Fani, M., Talebi, S., 2022. Green tax as a path to greener economy: A game theory approach on energy and final goods in Iran. *Renewable and Sustainable Energy Reviews,* 156, 111968. https://doi.org/10.1016/j.rser.2021.111968

North, E.J., Halden, R.U., 2013. Plastics and environmental health: The road ahead. *Reviews on Environmental Health,* 28(1), 1–18. https://doi.org/10.1515/reveh-2012-0030

Pandey, A., 2023. Beyond plastic: 5 Indian startups creating sustainable packaging from seaweed, bagasse and more! The Better India, 28 July. Online at: https://thebetterindia.com/406959/seaweed-plastic-packaging-alternatives-india-startups/

Pereyra-Camacho, M., Pardo, I., 2024. Plastics and the sustainable development goals: From waste to wealth with microbial recycling and upcycling. *Microbial Biotechnology,* 17(4), e14459. https://doi.org/10.1111/1751-7915.14459

Pilapitiya, P.G.C.N.T., Ratnayake, A.S., 2024. The world of plastic waste: A review. *Cleaner Materials,* 11, 100220. https://doi.org/10.1016/j.clema.2024.100220

Pla Industries, 2023. *Biodegradable plastic bags manufacturers in India*. Online at: https://plamfg.com/blog/biodegradable-plastic-bags-manufacturers-in-india/

Prieto, A., Escapa, I.F., Martínez, V., Dinjaski, N., Herencias, C., de la Peña, F., Tarazona, N., Revelles, O., 2016. A holistic view of polyhydroxyalkanoate metabolism in *Pseudomonas putida*. *Environmental Microbiology,* 18(2), 341–357. https://doi.org/10.1111/1462-2920.12760

PTI, 2019. Centre notifies plastic waste management rules, asks manufacturers, brand owners to collect waste. The Times of India, 5 June. Online at: https://timesofindia.indiatimes.com/home/environment/pollution/centre-notifies-plastic-waste-management-rules-asks-manufacturers-brand-owners-to-collect-waste/articleshow/68133589.cms

Ramaswamy, V., Sharma, H.R., 2011. Plastic bags - Threat to environment and cattle health: A retrospective study from Gondar city of Ethiopia. *International Journal of Integrative Biology,* 2, 7–12. http://www.iioab.org/SPI-1(EBT)/Ramaswamy-IIOABJ-2%20(1)-(SP1)-7-12p.pdf

Rosenboom, J.G., Langer, R., Traverso, G., 2022. Bioplastics for a circular economy. *Nature Reviews Materials,* 7, 117–137. https://doi.org/10.1038/s41578-021-00407-8

Santana, I., Félix, M., Bengoechea, C., 2024. Seaweed as basis of eco-sustainable plastic materials: Focus on alginate. *Polymers,* 16, 1662. https://doi.org/10.3390/polym16121662

Serrano-Aguirre, L., Prieto, M.A., 2024. Can bioplastics always offer a truly sustainable alternative to fossil-based plastics? *Microbial Biotechnology,* 17(4), e14458. https://doi.org/10.1111/1751-7915.14458

Sharma, R., Mondal, AS., Trivedi, N., 2025. Bioplastic from seaweeds: Current status and future perspectives. pp. 320–345. In: Trivedi, N., Reddy, C., Critchley, AT., (eds), *Recent Advances in Seaweed Biotechnology.* Springer, Singapore. https://doi.org/10.1007/978-981-96-0519-4_16

Sussarellu, R., Suquet, M., Thomas, Y., Lambert, C., Fabioux, C., Pernet, M.E., Le Goïc, N., Quillien, V., Mingant, C., Epelboin, Y., Corporeau, C., Guyomarch, J., Robbens, J., Paul-Pont, I., Soudant, P., Huvet, A., 2016. Oyster reproduction is affected by exposure to polystyrene microplastics. *Proceedings of the National Academy of Sciences,* 113(9), 2430–2435. https://doi.org/10.1073/pnas.1519019113

Thompson, R.C., Moore, C.J., vom Saal, F.S., Swan, S.H., 2009. Plastics, the environment and human health. *Philosophical Transactions of the Royal Society of London B Biological Sciences,* 364, 2153-2166. https://doi.org/10.1098/rstb.2009.0053

Torrejon, V.M., Fernando, S., Roy, U.K., Onwukwe, U., Anguilano L., 2025. Transforming seaweed into bioplastics: A review of cultivation, harvesting and processing methods. *Applied Phycology,* 6, 52–73. https://doi.org/10.1080/26388081.2024.2435035

United Nations Environment Programme, 2020. Country profile: Cambodia. SEA circular Project. Online at: https://www.sea-circular.org/wp-content/uploads/2020/05/SEA-circular-Country-Profile_CAMBODIA.pdf

United Nations Environment Programme, 2024. *End plastic pollution*: Towards an international legally binding instrument. Online at: https://www.unep.org/inc-plastic-pollution

Vadera, S., Khan, S., 2021. A critical analysis of rising global demand of plastics and its adverse impact on environment sustainability. *Journal of Environmental Pollution and Management,* 3, 1–12.

Werorilangi, S., Hovey, R., Umar, W., Hasyim, H., Harusi, N.M.R., Dexter, K.F., Langford, A., Ruhon, R., Zach, Z., 2023. End of life of plastics used in seaweed aquaculture in South Sulawesi. The Australia-Indonesia Centre. https://pair.australiaindonesiacentre.org/wp-content/uploads/2024/01/PAIR_End-of-life-of-plastics-used-in-seaweed-aquaculture-in-South-Sulawesi.pdf

Woods, J.S., Verones, F., Jolliet, O., Vázquez-Rowe, I., Boulay, A.M., 2021. A framework for the assessment of marine litter impacts in life cycle impact assessment. *Ecological Indicators,* 129, 107918. https://doi.org/10.1016/j.ecolind.2021.107918

WTS Global, 2024. *Plastic taxation in Europe*. Online at: https://wts.com/global/publishing-article/20240508-plastic-taxation-europe-update-2024~publishing-article

Xiao, X., Liu, S., Li, L., Li, R., Zhao, X., Yin, N., She, X., Peijnenburg, W., Cui, X., Luo, Y., 2024. Seaweeds as a major source of dietary microplastics exposure in East Asia. *Food Chemistry,* 450, 139317. https://doi.org/10.1016/j.foodchem.2024.139317

Zhang, L., Jing, Z., Xiaofeng, R., 2017. Natural fiber-based biocomposites. pp. 31–70. In: Jawaid, M., Sapuan, S., Alothman, O., (eds), *Green Biocomposites. Green Energy and Technology.* Springer, Cham. https://doi.org/10.1007/978-3-319-46610-1_3

Zhao, C., Liu, M., Du, H., Gong, Y., 2021. The evolutionary trend and impact of global plastic waste trade network. *Sustainability,* 13(7), 3662. https://doi.org/10.3390/su13073662

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