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Contribution of seaweed farming to the mitigation of greenhouse gas emissions and microplastics pollution

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ABSTRACT

In recent decades, human activities have caused many adverse environmental issues that continue to pose a threat to the earth's ecosystems. Global warming and the widespread detection of microplastics are examples of these activities, both of which are largely associated with the use of fossil fuels. Farming and utilization of seaweeds for commercial and industrial applications presents a potential solution to alleviate these problems. Seaweed farming can sequester CO_2 from the atmosphere without competing with human activities that rely on agricultural land and water resources and will therefore not contribute to deforestation. Polysaccharides extracted from seaweeds are raw materials for some biodegradable bioplastics and their use may limit the generation of microplastics in the environment. Under the right conditions, the degradation of seaweed bioplastics also produces fewer greenhouse gas emissions compared to the degradation of conventional plastics. However, the commercial acceptance of seaweed polymers is currently hindered by the relatively high manufacturing cost and quality of the final products. Therefore, further research is essential to advance the development of seaweed farming and the use of seaweed polymers as potential replacements for fossil-fuel based polymers.

1. Introduction

Activities aimed at increasing human welfare have led to many serious environmental issues, especially following the industrial revolution [1,2]. For example, the production, use and release of various anthropogenic substances has adversely impacted the ozone layer allowing more high-frequency ultraviolet (UV) radiation to reach the ground and impose negative impacts on the people's health [3]. Synthetic persistent organic pollutants and their derivatives have further caused long-term regional and local pollution of water systems on a global scale for many decades [4]. Other human activities have altered the landscape and associated vegetation and have changed the water balance and processes that control water quality [5]. This has resulted in an indisputable decline in global flora and fauna biodiversity [6]. In addition, >85 % of the earth's deltas have experienced severe flooding, and it is conservatively estimated that the delta surface area vulnerable to flooding could increase by 50 % in the 21st century [7].

Significant efforts have been made globally to repair some of the environmental damage caused by human activities and these efforts have achieved some successes [8–11]. One of the most remarkable achievements is the recovery of the hole in the ozone layer above the Antarctic region following global collaborations to restrict ozone-depleting substances [12,13]. However, there are still many emerging and current environmental challenges that require considerable resources and global co-operation to address. Global warming incurred by the greenhouse gas emissions and microplastics from wide use of the synthetic polymers are two global issues impact the pedosphere, hydrosphere, and atmosphere of the environment, which require worldwide collaboration to solve [14].

Seaweed farming is emerging as a potential solution for the two issues facing the global environment. The farmed seaweeds can be used to produce polysaccharides, which have a wide range of industries and products including food, pharmaceuticals, and medical applications [15]. In addition, seaweed farming from both from wild stocks and aquaculture, can effectively harvest CO_2 from the atmosphere with an estimated annual global uptake of 1.5 Gt of carbon via the net-production of seaweed in the last decade [16]. Given the potential for seaweed farming to mitigate some of the current and emerging

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environmental issues, this review presents the potential of this practice to positively influence some of the most urgent concerns facing the global environment, such as the global warming and microplastic pollutions.

2. Exigent environmental issues

Numerous processes are known contributors to the environmental issues facing global communities. These include global warming, pollution and waste disposal, depletion of the ozone layer and natural resources, loss of biodiversity and deforestation [17]. These processes are related to human activities and global warming is a sum of many of these processes. The emergence of microplastics in the environment is a more recent and highly visible issue and the impacts on flora, fauna and human health are a growing concern [18].

2.1. Global warming

The temperature of our planet has increased by 1.2 ± 0.1 °C, compared to preindustrial values [19,20], with an increase of 0.8 °C occurring in just the past 40 years [21]. The United Nations report that weather related disasters accounted for 90 % of all disasters globally from 1995 to 2015, which resulted in the loss of about 606,000 lives with a further 4.1 billion people injured and/or displaced from their homes [22]. Other reports claim that global warming is accelerating with a doubling in weather-related disasters from 2005 to 2014, in comparison with those from 1985 to 1994 [23].

Global warming can be assessed by measurement of surface air temperature (SAT), which is a widely accepted climate variable. Anthropogenic emissions of GHGs are considered as a main trigger of current climate change, which is one of the world's more serious challenges [24]. A relationship between global temperatures and GHG concentrations has been established throughout history [25]. One recent study reported that from 1958 to 2005 that the rate of GHG emissions-induced global warming was 0.014 °C/yr [26]. It is estimated that at the current rate of GHG emissions, the SAT warming may reach 4.8 °C by 2100 [23].

2.2. Microplastics

Microplastics are emerging pollutants which are ubiquitously distributed in oceans, estuaries, freshwater and ice, and pose a serious potential threat to ecology [27]. They are fragments of plastics with size in range of 1 to 5000 μm, and captured widespread attention after massive "garbage patches" were observed in the world's great oceanic gyres [28]. Microplastics are typically not collected for recycling or disposal from the environment, and are potentially bio-accumulating pollutants that compromise the capability of the oceans to support life [27]. Floating microplastics are commonly quantified up to 104 particles per m^3 in coastal regions, and invariably accumulate in the sediment [29]. The influence of microplastics on marine ecosystems are not reversible and are pervasive, and have the potential to cause widespread ecological disruptions, such as blooming of harmful algal species, viruses and microbial communities and facilitating invasion of alien species [30]. However, there are still many uncertain impacts to the ecosystem that can result from microplastics, such as their potential toxicological risks [31].

Microplastics are derived from two main sources: (i) intentionally manufactured microbeads used in cosmetics, toothpaste or air-blasting technology, which enter the marine system majorly through wastewater treatment plants [32]; and (ii) from the breakdown of synthetic polymeric items, such as plastic waste, chemical fibres shed from textiles, or tyre dusts from tyre wear [32]. The latter source is considered to be the major contributor to microplastic pollution [33,34]. Microplastics can fragment further into >1000 times more nanoparticles (<1 μm) over time [35,36].

Van Sebille et al. estimated that there were 15–51 × 10^{12} or 93–236,000 tons of microplastic particles in the ocean in 2014 [37], and Jambeck et al. suggested that plastic fragments entering the ocean annually range from 4.8 to 12.7 million tons and will increase tenfold by 2025 [34]. Microplastics have also been found in pristine locations including Arctic Sea ice, Antarctic remote mountain ranges and deep ocean trenches [38–41]. These days, the focus of research in this area is shifting from addressing the extent of microplastic contamination to tracking the formation, transport, fate, organism exposure, and ecosystem effects of microplastics [42].

2.3. Connection of GHG emission and microplastics

Global warming incurred by the GHG emission accelerates the generation and distribution of microplastics. Elevated temperature enhances the degradation of synthetic polymers leading to more fragmentation and smaller microplastic particles in the environment [43]. Microplastics will also be transported and dispersed quickly and widely by the extreme weather such as storms, hurricanes and floods caused by global warming [44].

Microplastics enter water bodies and threaten aquatic life and release GHG such as CO_2, methane, and ethylene during their degradation [45]. Microplastics also affect the respiration and photosynthesis ability of marine life, which could affect the capacity of ocean retaining biocarbon/CO_2 [46].

3. Mitigating anthropogenic impacts on the environment

As the awareness of human behaviours affecting the environment is increasing, many efforts have been employed to mitigate the emerging catastrophic disasters via global collaborations. Although there are some achievements, considerably more work must be implemented to avoid further deterioration of our environment and potentially repair some of the damage.

3.1. Slowing and reversing global warming

3.1.1. Lowering GHG emissions

There is no doubt that the best way to slow global warming is to lower anthropogenic emissions of GHGs [47]. However, many current GHG emissions relate to essential human activities and can therefore not be reduced or eliminated quickly without other consequences [48–50].

Reducing the consumption of products originating from fossil fuels can, therefore, minimise the conversion of fixed carbon into CO_2. Although there are still some barriers to alternative fuels and energy sources, wind farms and solar farms are starting to replace coal and gas fired plants as primary energy producers [51,52]. Development of efficient electricity storage systems can buffer the impacts of often less reliable energy obtained from alternative sources and can facilitate the implementation of more renewable energy supplies [53].

3.1.2. Capturing GHG emissions

GHG capture is another approach to slow the increase and accumulation of GHGs in the atmosphere. The process of carbon capture and storage (CCS) has been used to reduce CO_2 emissions from power plants [54], but it is an energy-intensive process and requires additional fossil fuel consumption to enable the capture of CO_2 [55].

Terrestrial vegetation also can absorb CO_2 and suppress the emission of other GHGs such as methane from the soil [56]. Plants adsorb CO_2 from the atmosphere and fix the carbon through photosynthesis, and it is estimated that 500 billion tons of CO_2 are fixed annually by the earth's primary biological terrestrial productivity [57]. In general, the conversion of carbon fixed in the fossil fuels into CO_2 will continue to increase the overall CO_2 in the atmosphere during carbon circulation [58]. Therefore, to obtain an equilibrium, the amount of CO_2 released into the atmosphere must be equivalent to or less than that being sequestered by biomass or other means. However, it has been reported that the climate mitigation role of forests could also be compromised due to the release of N_2O gases that have a global warming impact 298 times that of an equivalent weight of CO_2 (CO_2-eq) [59].

Oceans are the largest long-term carbon sink on the earth, and they store and cycle around 93 % (40 trillion tonnes) of CO_2. Marine ecosystems capture and store approximately 50 % of the carbon in the atmosphere which is either fixed or sequestered, with coastal ecosystems accounting for up to 70 % of the carbon permanently stored in the marine environment [60]. Living marine organisms also capture 55 % of the biological carbon in the world, known as "blue carbon", and account for 47 % of the total carbon buried in ocean sediments [60]. Hence, concurrent with other approaches, conservation of marine ecosystems is vital to buffer increasing GHGs in the atmosphere.

3.2. Mitigation of microplastics

Plastics used on land and sea contribute up to 80 % and 20 % of microplastics respectively. Microplastics are distributed over large areas due to their small size and low density making them easily transportable and their durability results in a long lifetime [61]. In addition to their ubiquitous distribution, microplastics are also associated with the emission of GHGs from the soil due to their influence on the microbial community structure in soils [62,63].

3.2.1. Management of waste plastics

Plastic trash islands and garbage patches discovered in ocean gyres has attracted much conversation and subsequent research. Some schemes have been proposed to remediate ocean plastics such as harvesting the debris and converting the plastic to fuel by pyrolysis onboard ocean-going barges, or by biologically decomposing the plastics [64]. Furthermore, studies show that macroalgal can also trap the microplastics through twining, attachment, embedment and wrapping, which could partially alleviate the influence of microplastics on marine ecosystems [65,66]. However, these approaches are limited in feasibility due to excessive costs, ecological impacts, or suitability in real ocean conditions. At the G7 meeting held in Germany 2015, the only viable program presented for ocean clean-up was Fishing for Litter (https://fishingforlitter.org/), which was described as "a useful last option in the hierarchy, but can only address certain types of marine litter" [67].

Since land-based sources of microplastics are four times greater than of that of marine sources, it would be more feasible to focus efforts on the control the former sources. The first step in the mitigation of microplastics is to identify their sources. The second step is proper management of the identified sources via regulation and technological innovations. In regulations enforced in the USA, a standard method is provided for quantification of microbeads [68,69]. A summary of terrestrial sources and potential management for the mitigation of microplastics from these sources are shown in Table 1.

3.2.2. Biodegradable substitutes for common plastics

Bioplastics have been in production as early as the 1930s when soy-based phenolic resins were first used by Henry Ford in the development of the "soybean car" in an effort to combine agriculture and industry [70]. The term bioplastics are used to describe plastic materials that are biodegradable and/or bio-based with the latter term defined as materials derived from biomass. In general, the production and lifecycle of most bioplastics results in no net increase in GHG emissions. However, not all bioplastics are inherently biodegradable. For example, bio-polyolefins and bio-polyesters can be derived from biomass feedstocks but they have the same properties as their petroleum-based analogues and are therefore not readily biodegradable [71]. As such, non-biodegradable polymers, regardless of their origins, are the primary sources of microplastics.

The conditions under which biodegradable plastics decompose also vary widely [72,73]. In order for biodegradable plastics to become more acceptable, formal agreements and government policies are needed to ensure the production, use, and disposal of biodegradable plastics is a viable alternative to current commodity plastics [74].

Table 1
Sources, measurements, and strategies for upstream mitigation of microplastics [64].

Source	Potential mitigation
Plastic beads in cosmetic products	Using alternatives
Mishandling plastic pellets for production	Regulating the operation procedure and setting up a remedy plan
Industrial abrasives	Improvement of containment and recovery, and employment of alternatives
Film, pots and pipes used by agriculture	Improvement of plastic recycling, and employment of biodegradable plastics
Tyre dust	Technological advances in tyre manufacturing and road surfaces
Litters of small plastic items	Enforcement of fines for littering and consumer education
Degradation and fragmentation of terrestrial plastic waste	Improvement of legislation and law enforcement and employment of alternatives
Sewage effluent (synthetic fibres)	Improvement of laundry filtration, and fabric innovation
Combined sewage overflow (large items)	Infrastructure improvement

The limited commercial application of biodegradable plastics is evidenced by the vast quantities of petroleum-based plastics that are produced and used in packaging and other industrial applications. In applications for which materials are impossible or costly to recover and recycle, such as single use or disposable packaging materials, biodegradable plastics could be suitable alternatives to conventional plastics. By replacing some of these materials with biodegradable bioplastics, the release of microplastics into the environment from abandoned plastics could potentially be reduced.

4. Role of seaweeds in GHG and microplastic mitigation

4.1. Use of seaweeds to harvest GHG emissions

It was previously believed that seaweeds would decompose completely in the ocean and cannot capture carbon. Seaweeds were therefore not considered a significant solution for permanently sequestering and storing environmental carbon in deep ocean floors or sediments [75,76]. However, it has been demonstrated recently that seaweed is an excellent carbon sink [77,78] with estimates that marine algae transform nearly 50 Gt of carbon dioxide each year from the atmosphere and convert it into biomass [79,80]. It is also well known that seaweeds are comprised of 30–80 % carbohydrates in their biomass as storage of carbon and energy [81–83]. The seaweed ecosystem therefore acts as a carbon sink since carbon released by decaying seaweeds can be trapped in sediments or migrate to the deep sea [76].

Coastal vegetated ecosystems contribute substantially to global carbon sequestration via the storage of "blue carbon", which has been recognised in many countries with the planting of mangrove forests, tidal marshes, and seagrasses [84]. In addition to capturing a significant amount of CO_2, seaweed ecosystems play other important roles in coastal environments such as remediation of contamination and providing habitation for other marine organisms [85]. Seaweeds also protect the coastlines from erosion, can be used as food sources, and control acidification and ocean deoxygenation, which are significant for climate mitigation [86].

Seaweed crops can also be used as raw material for biofuel production, with a potential CO_2 mitigation capacity by lowering conversion of carbon fixed in fossil fuels into CO_2. It has been estimated that 961 kg of CO_2 can be harvested from the atmosphere for every ton of seaweed (dry weight) used in biofuel production [87]. This equates to about 1500 tons of CO_2 that can be sequestrated annually from every square kilometre of farmed seaweed, from which the CO_2 generated from the production activities has been subtracted from the estimation [88]. Hence, there is great potential for utilising seaweed farming as an approach to slow the increase of CO_2 in the atmosphere [89]. Furthermore, agriculture has historically largely relied on converting pristine land to farmlands, or resource extraction by clearing or thinning wild vegetation to meet human resource demands [90]. This has rapidly exacerbated climate change, pollution, acidification, biodiversity loss, and ocean acidification [91]. Compared to farming on land, seaweed farming does not typically replace the original vegetation and the use of native seaweeds would have much less impact on the environment. However, like most farming practices, seaweeds suitable for farming are the types that are the most efficient for production of foods, plastics and that give the highest economic return.

Recently, however, some researchers have disputed the suggestion that seaweeds can mitigate carbon dioxide in the atmosphere [92]. If an ecosystem under equilibrium is considered, the total carbon mass would not be expected to vary greatly. However, there would be 2.4–20.1 % of carbon transferred to permanently fixed carbon and/or refractory dissolved organic carbon (RDOC) with life span 4000–6000 years [86,93,94], which would have some influence on reducing CO_2 in the atmosphere. Fig. 1 presents a simplified schematic of carbon circulation, and it can be seen two primary sources of CO_2 are closely related to human activities. These are the consumption of fossil fuels (permanently fixed carbon) and the degradation and/or metabolism of temporarily fixed carbon by living organisms (humans, plants, animals etc.). The conversion of permanently fixed carbon to CO_2 is essentially an irreversible process as the formation of permanently fixed carbon is a slow process. However, based on the mass balance, the conversion process can reduce CO_2 by increasing the overall amount of temporarily fixed carbon since nearly all carbon in living organisms is obtained directly or indirectly from CO_2 through photosynthesis. Hence, increasing the total carbon mass of living organisms can mitigate CO_2 emission as long as there is no additional consumption of permanently fixed carbon (i.e. production/use of synthetic fertilizers, energy consumption etc.). By expanding seaweed farms, new CO_2 consumers can be introduced, and more carbon can be retained as temporarily fixed carbon and therefore suppressing the increase in CO_2 released to the atmosphere. Using organic materials obtained from seaweeds such as their biopolymers, can further extend the duration that carbon is temporarily fixed and subsequently slow the conversion of carbon into CO_2.

However, there are still some questions and conflicting views regarding the practice of farming seaweeds for CO_2 sequestration. Hurd et al. [95,96] believed that the air-sea CO_2 equilibrium is a critic issue needs to be more fully understood to further promote CO_2 sequestration by seaweeds. Troell et al. [97] recognised that seaweeds only temporarily fix carbon due to the high turnover rate, which is much faster than that of woody biomass, and therefore limits the potential to lock up carbon in the long-term. Chopin [98] recommended against the practice of sequestering seaweed to deep sea until its efficacy is established.

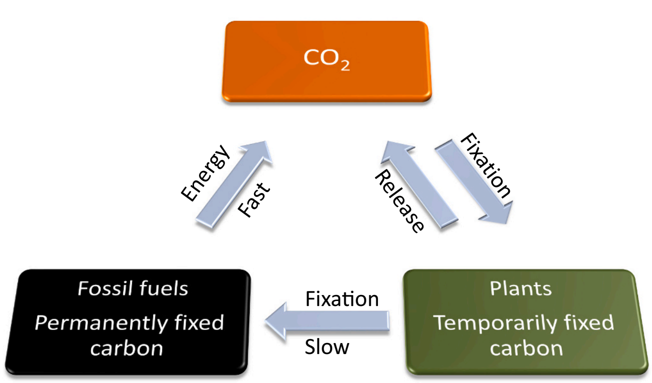

Fig. 1. Simplified carbon circulation.

Although there is some evidence that the practice can store carbon in sediments located near farming sites [99], the ability of seaweed farming to remove CO2 from the air is still in need of robust quantification [100].

Life cycle assessment [101,102] can be used to further evaluate the conflicting arguments for and against seaweed farming for sequestering CO_2. This approach can assess and quantify the environmental impacts associated with seaweed cultivation and utilization, can identify the potential of various product chains, and can compare end-of-life pathways for these products.

4.2. *Seaweed farming*

4.2.1. *Global seaweed cultivation*

Seaweeds have been commercially farmed for a very long time and as ocean originating commodities, seaweeds are diverse in species. Among the ca. 200 species of seaweeds that are cultivated worldwide [103], brown algae: *Laminaria japonica* and *Undaria pinnatifida*; red algae: *Porphyra*, *Eucheuma*, *Kappaphycus* and *Gracilaria*; and green algae: *Monostroma* and *Enteromorpha* are most common [104]. Table 2 lists the global seaweed production from different continents and top ten countries in 2019 [105]. The total annual global seaweed production (wet weight) was approximately 36 million ton, of which 97.38 % was produced in Asia with 97.0 % farmed seaweeds. China was the largest seaweed producer contributing 56.75 % of the overall seaweeds worldwide and 58.02 % of farmed seaweeds. In general, seaweed farming and cultivation dominates global seaweed production, and this has significantly increased over the past 50 years. In 2019, wild seaweed production was 1.1 million ton, the same as that in 1969 [106], but it was only about 3 % of the total seaweed produced compared to 50 % in 1969.

Based on a very simplistic calculation (12 % C on Dry weight (DW) basis, DW = 10 % of fresh weight), it will sequester 1.4 million ton of CO_2 by the farmed seaweeds.

4.2.2. *Cultivation of different seaweed types*

The production of different seaweed types in 2020 and 1959 are shown in Table 3 [105,107–109]. Compared to the dominant brown and red seaweeds, production of the green seaweeds from cultivation was negligible in 1950 and represented only 0.07 % of the total cultivated seaweed in 2020.

From 1950 to 2020, the overall growth in the cultivation of brown seaweeds was 11 % and in general, brown seaweed cultivation is dominated by two cold-water genera, kelp (*Laminaria japonica/Saccharina latissima*) and wakame (*undaria pinnatifida*), of which about 88 % were produced by China in 2020 [105,109]. Brown seaweeds are mostly used as food for humans and animals, and they are also used as raw materials to produce alginate, health supplements, cosmetic additives, polymers for biotechnological and pharmaceutical applications, and compostable bio-packaging [110].

From 1950 to 2019, the percentage of cultivated seaweeds that were derived from red seaweeds increased by 10 % globally. Two tropical species of red seaweeds, *Kappaphycus/Eucheuma* and *Gracilaria*, and one cold-water species, *Porphyra*, are most widely cultivated. All three species of red seaweeds are cultivated for human consumption, however, *Gracilaria* and *Kappaphycus/Eucheuma* are used mostly as raw materials for seaweed-based hydrocolloids agar and carrageenan respectively [106,111,112].

4.2.3. *Impact of seaweed farming on the existing ecosystem*

Currently, there is not enough knowledge on the influence of seaweed farming on ecosystems [113]. With the ever-increasing number of microplastics in the ocean, a shift to biodegradable polymers may be beneficial to marine organisms due to the smaller effect found when compared to petroleum-derived polymers in this study. In some countries, farmed seaweeds have been considered as invasive species [114].

Table 2
Global wild and cultivated seaweed production [105].

Country/area	Total seaweed production (wet weight)		Seaweed cultivation (wet weight)		Wild seaweed production (wet weight)	
	(Ton)	Share of world production (%)	(Ton)	Share of total production (%)	(Ton)	Share of total production (%)
World	35,762,504	100.00	34,679,134	96.97	1,083,370	3
Asia	34,826,750	97.38	34,513,223	99.10	313,527	1
Americas	487,241	1.36	22,856	4.69	464,385	95
Europe	287,033	0.80	11,125	3.88	275,908	96
Africa	144,909	0.41	117,791	81.29	27,118	19
Oceania	16,572	0.05	14,140	85.32	2432	15
By country						
1. China	20,296,592	56.75	20,122,142	99.14	174,450	1
2. Indonesia	9,962,900	27.86	9,918,400	99.55	44,500	0
3. Republic of Korea	1,821,475	5.09	1,812,765	99.52	8710	0
4. Philippines	1500,326	4.20	1,499,961	99.98	365	0
5. Democratic People's Republic of Korea	603,000	1.69	603,000	100.00	0	0
6. Chile	426,605	1.19	21,679	5.08	404,926	95
7. Japan	412,300	1.15	345,500	83.80	66,800	16
8. Malaysia	188,110	0.53	188,110	100.00	0	0
9. Norway	163,197	0.46	117	0.07	163,080	100
10. United Republic of Tanzania	106,069	0.30	106,069	100.00	0	0

Table 3
Comparison of seaweed cultivation in 1950 and 2020 [105,107–109].

Seaweed type	Production year			
	1950		2020	
	Wet weight (Ton)	Percentage (%)	Wet weight (Ton)	Percentage (%)
Brown seaweeds	13,000	38.2	16,800,000	48
Red seaweeds	21,000	61.8	18,100,000	51.3
Green seaweeds	0	0	23,000	0.07

However, by moving seaweed farms to deep water and farming native seaweeds may mitigate the impacts of this livelihood.

4.3. Seaweed polymers

Seaweed polymers are biodegradable and could also break down to the size of microplastics. However, compared with petroleum-derived microplastics, it has been shown that biodegradable polymers in the microplastic size range have less effect on marine organisms, besides being degradable in a much shorter period [115].

4.3.1. Sources of seaweed polymers

Seaweeds contain 10–20 % dry mass, which is composed of approximately 50 % carbohydrates mainly in form of polysaccharides, 1–3 % lipids, and 7–38 % minerals, and 10–47 % protein [116,117]. Among the different seaweed types, red and brown seaweeds are the most important sources of seaweed polymers, which are polysaccharides mainly including agar, carrageenan, and alginate [118]. These polymers or hydrocolloids are normally extracted from dried seaweed biomass via multistage separation and purification.

Red seaweeds, *Gracilaria*, *Gelidium* and *Pterocladia/Gelidiella*, are commercially used for the extraction of agar [119] with the best quality agar extracted from *Gelidium* species. However, *Gelidium* has not been successfully commercially cultivated to date and natural resources are limited compared with *Gracilaria* species [120,121]. Other red seaweed species, *Kappaphycus alvarezii*, *Eucheuma denticulatum* and *Betaphycus gelatinae* are the most important resources for commercial carrageenan extraction [122]. *Kappaphycus alvarezii* and *Eucheuma denticulatum* have been cultivated to meet the increasing demands of carrageenan and the characteristic properties of carrageenan compositions vary significantly depending on the red seaweed species source [123]. Brown seaweed species, *Laminaria hyperborean*, *Macrocystis pyrifera*, *Laminaria digitata* and *Ascophyllum nodosum* are mainly used for commercial alginate production. Of these main sources of alginate, *Laminaria hyperborean*, *Macrocystis pyrifera*, *Laminaria digitata* seaweeds have been successfully farmed and cultivated [124].

4.3.2. Seaweed polymer extraction

Heat-assisted extraction (HAE) and Soxhlet extraction methods are commonly used for seaweed polymer isolation. The process of HAE utilises solvents to extract compounds from the solid to liquid phase with the use of heat and/or agitation [125]. For the extraction of seaweed polymers, hot water and acidic solutions are most commonly used as solvents, and extraction temperatures normally vary from room temperature to 100 °C with extraction times usually ranging from several hours up to 48 h [126]. The Soxhlet extraction method utilises continuous solvent flow during the process, but it is usually used to remove impurities prior to the extraction [127]. Hot water is commonly used as a solvent in the extraction for a duration of 2–3 h, in which chemicals, such as $CaCl_2$, are also added to increase the extraction efficiency [128]. However, both methods require long overall extraction times and high temperatures that may cause compound degradation and consume large amounts of solvents that can be toxic [125,129]. A general schematic flowchart of the process for seaweed polymer extraction and purification is shown in Fig. 2.

4.3.3. Seaweed polymer applications

The most commonly used seaweed extracts are alginate, carrageenan and agar, and these are widely used for food packaging, tissue

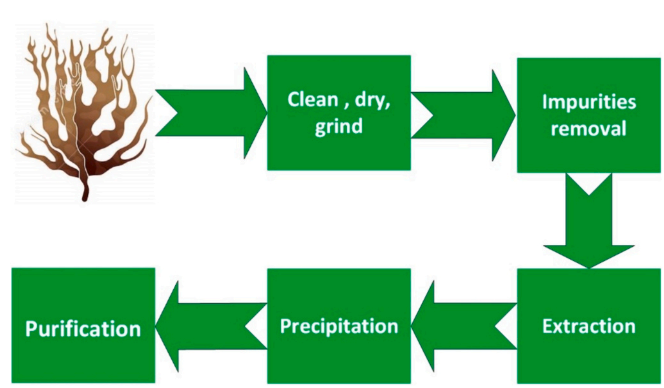

Fig. 2. Schematic of seaweed polymer extraction.

engineering, drug delivery and wound dressing [15,130] in addition to many other uses. Agars are linear polysaccharide mixtures of agarose and agaropectin, in which agarose makes up about 70 % of the mixture and is responsible for the gelling and thickening properties [120,131]. It can be used for food and pharmaceutical applications, and can also be used for paper sizing, coatings, adhesives, textile printing/dyeing, casting and tooth impression [132]. Agar extracted from *Gracilaria chilensis* (red seaweed) can be used as a substitute for gelatine in confectionery with very high sugar content due to the ability of sugar (sucrose) to increase agar gel strength [133].

Alginates are linear polysaccharides forming the main cell wall and cell matric of almost all brown seaweeds, and providing both flexibility and strength to the seaweeds [134]. Alginates consist of β-D-mannuronic acid (M) and α-L-guluronic acid (G) units that can be present in different configurations and ratios. The M/G ratio has a major impact on the physicochemical properties of alginate where those with high G contents are strong and brittle and those with high M contents are more flexible [135,136]. In addition to extensive uses in food and pharmaceutical applications, alginate also can be employed in other industries such as electronics, packaging and textiles [137,138].

Carrageenan has a similar structure to agar, and is composed mainly of potassium, sodium, magnesium, and calcium salts of sulphated esters of galactose and 3,6-anhydro-galactose copolymers [139]. According to the number and position of sulphate groups in the repeating units, there are six types of carrageenan, known as μ, ν, λ, κ, ι and θ carrageenan, in which κ, ι and λ are more widely commercially available [119,140]. The ester sulphate content ranges between 25 % and 35 % among carrageenan types, in which κ-carrageenan and λ-carrageenan respectively show the lowest and the highest level of sulfation respectively. The anionic sulphate groups are responsible for the thickening and stabilizing properties of carrageenan by binding to positively charged protein groups in foods [141]. Similar to the other seaweed polymers, carrageenan is widely used in the food, cosmetics and pharmaceutical industries, mostly as a thickener and gelling agent [142,143].

The main physicochemical properties of these seaweed polymers are listed in Table 4. Agar possesses excellent gel strength (7–10 kPa) which is 2–10 times greater than that of carrageenan (1–3.5 kPa). It can form strong and rigid gels at room temperature and remain firm at 65 °C due to the high melting point (85–95 °C) which is associated with the lower content of anionic sulphate. Alginate has both the highest melting point (>300 °C) and gel strength of 123–679 kPa, however, the tensile strength is low compared to that of typical polyethylene films used in packaging applications (~8.65 MPa) [144]. It is therefore challenging to use seaweed polymers directly in applications where high mechanical strength is required, such for textiles and packaging. However, there are significant strategies that can be employed to improve the overall properties and performance of seaweed polymer films.

The general functional characteristics and application of the common seaweed polymers is shown in Table 5. It is evident that the primary applications of these seaweed polymers are related to the food and pharmaceutical industries where they find use as auxiliary materials for gel formation, filling and thickening. However, they can also be employed as main raw materials for packaging, textiles and adsorbents where they can potentially replace petroleum-based products.

Table 5
General properties of common seaweed polymers [145,146,148–150,153,154].

Polymers	Functional properties	Applications		
		Food and beverages	Pharmaceutical and biotechnology	Other industries
Alginate	• Fast absorption of water • Excellent gelling, stabilizing, thickening agent • Thermo-irreversible (with the presence of calcium)	Thickener, gel	Dental impressions, wound dressing, medicine, additives, antacid, prosthetic devices, sutures, drug delivery system	Adsorbent for wastewater treatment, paper and textile industry, emulsifier, lubricant, refining, filling agent, packaging
Agar	• Excellent gelling agent • High temperature resistance • Thermo-reversible	Stabilizer, gel, alternative to gelatine	Dental impressions, intestinal regulator, excipient, growth media, gel electrophoresis, bulk laxative	Textile, paper making, winemaking
Carrageenan	• Thermo-reversible • Good gelling, stabilizing, emulsifying, thickening and water holding properties	Gels, alternative to gelatine, thickener	Toothpaste, cosmetics, inhibitor of papilloma, controlled released system, lotion and cream, suspending agents, eye drops, suppositories	Cosmetic and paint industries, packaging

4.3.4. Seaweed polymer packaging materials

Packaging materials dominate the waste generated from plastics [155] with single-use packaging particularly problematic world-wide. The different types of polysaccharides found in the seaweeds can be used to make bioplastics, which are reported to be more resistant to microwave radiation, less brittle and durable, and are especially popular in applications for the packaging sector due to their biodegradability [156]. Seaweed bioplastic shopping bags are already very common, and can be reused as organic waste bags being composted after initial use [157]. Seaweed polymeric films are typically fabricated by the solvent casting method, in which the seaweed polymer is dissolved with additives under stirring, cast onto plates and dried under set humidity to form films [158].

Although alginate, carrageenan and agar possess suitable film-forming properties, seaweed polymeric films generally exhibit relatively low barrier properties to water vapour and poor mechanical strength compared to fossil fuel originated polymers [159]. Hence, modification is generally required to improve the properties of seaweed films and mixing with other polymeric or inorganic materials is one of the most popular methods to form composite films suitable for packaging [160–162]. Nanoclays can form strong composite structures with intercalated silicate layers and the seaweed polymer matrix that can suppress water vapour diffusion and increase the tensile strength of the

Table 4
Physicochemical properties of the seaweed polymer [145–152].

Polymers	Gelling point (°C)	Melting point (°C)	Solubility	Gel strength (kPa)	Viscosity (mPa·s)	Appearance
Agar	32–45	85–95	Boiling water	7–10	10–100	Yellowish powder
Alginate	10–40	>300	Soluble in water	123–679	135–994	Yellowish powder
Carrageenan	30–50	50–70	Soluble in water	1–3.5	30–300	Yellowish powder

formed composite films [162]. By adding functional components, such as antimicrobial additives, seaweed based food packaging materials could possess different functions, such as inhibition to pathogen growth [163,164]. Other bioplastics, such as starch and cellulose can also be used to functionalise or reinforce various seaweed polymers [165,166].

Agar has excellent filming properties and can be used to prepare composite packaging films by adding different amounts of nanoclays and/or cellulose, with films widely used in food and pharmaceutical applications [162]. Alginate readily reacts with divalent and trivalent cations to form crosslinked structures, which are widely employed in the formation of alginate composite films. By incorporating starch into alginate prior to crosslinking, the formed composite films are reported to possess both excellent mechanical and barrier properties suitable for food packaging [15]. Composite films prepared from alginate, gelatine and whey protein isolate also show excellent mechanical and barrier properties for food packaging applications [167]. Of the three main commercial classes of carrageenan, κ-carrageenan is able to form strong, rigid gels in the presence of potassium ions and has been used for the formation of cohesive and transparent films [168].

Over recent years, many reviews and book chapters have been published that report developments in seaweed polymers and composites for various applications. In Fig. 3, the percentage of reviews published from 2018 to 2022 (five years) associated to film/packaging materials prepared from different seaweed polymers are shown [169–198]. It can be found that alginate and carrageenan are most studied seaweed polymers in film/packaging area. It is clear that the majority of research in this field is focused on improving the performance of materials so they may be viewed as a potential future replacement for conventional packaging. In addition, research has also been directed towards the use of active additives that can offer both improved physicomechanical performance and the enhancement of bioactivity that can ultimately extend the shelf-life of certain food products. The scope of work already completed in this field demonstrates the future of seaweed polymers for packaging, and the research that is needed to fully realise the potential of these natural and renewable resources.

4.3.5. Future perspectives of seaweed polymers

In comparison with conventional plastics, the manufacturing cost of seaweed polymers is currently much higher, and the functional quality is relatively poor with the exception of biodegradability. Some of the important challenges facing the industry and consumers with respect to the production and use of bioplastics include:

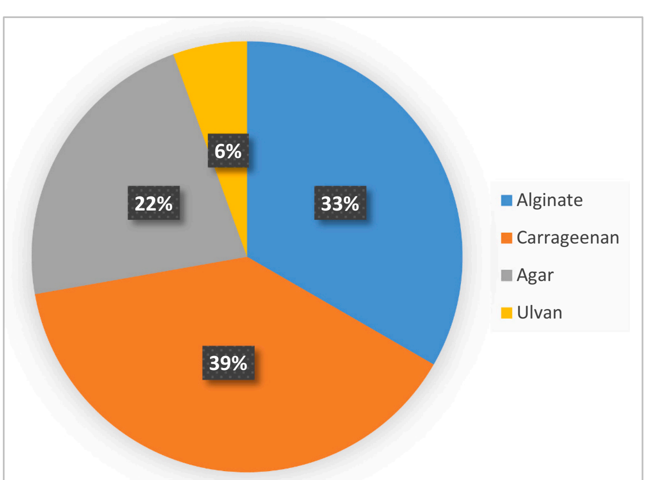

Fig. 3. Reviews and book chapters on the development of seaweed polymers for packaging.

- seaweed farming can potentially cause detrimental impacts on the marine environment;
- the production of seaweed can be affected by weather;
- extraction of seaweed polymers sometimes involves the use of chemicals that can cause environmental problems;
- seaweed polymers cannot currently be recycled and can contaminate domestic recycling streams when mixed with recyclable plastics;
- composting of seaweed polymer might require special conditions which may not be readily available in all locations;
- not all seaweed polymers are suitable for natural degradation and the impact of seaweed polymer microplastics is unknown;
- additives in seaweed polymers for functionalisation and reinforcement increase the overall manufacturing costs. When the seaweed polymer degrades, additives will leach out and might cause environmental issues.

However, these issues can be solved by a combination of government regulations and comprehensive research and development. By managing seaweed aquaculture ecosystems properly, coastal eutrophication and hypoxia due to the emission of excess nutrients could be suppressed to limit adverse environmental impacts [199]. In addition, by employing farming practices that utilise native seaweed varieties, further negative impacts on the marine ecosystem can be minimized. Although there are no specific policies to support the production or farming of seaweed as an alternative for the production of plastics components, there are stringent regulations and public demand for safe eco-friendly biopolymers around the world [200,201]. Seaweed polymers could be one of the candidates for the solution. Since both the production costs and functionality of synthetic plastics are currently superior to seaweed polymers, support from the government, industries, and the public are vital for progressing research and development of seaweed polymers as substitutes for conventional plastics. If these challenges are addressed, the broader implementation of seaweed polymers can offer a possible pathway to address climate change and reduce the distribution of microplastics in the environment.

5. Summary

Farming, cultivating and utilising seaweed polymers as potential substitutes for synthetic plastics can offer multiple environmental benefits by reducing emissions of both GHGs and the widespread accumulation of microplastics. Seaweed farming is progressing rapidly and is anticipated to contribute to current and emerging industrial sectors globally. In comparison with farming terrestrial crops for biopolymer production, seaweed farming potentially alleviates the burden on agricultural lands and reduces the environmental load with respect to the use of fertilizers and other chemicals. The use of seaweed polymers in many industries is already well-developed and common practice including extensive use in food and pharmaceutical applications. Although seaweed polymers have been used for some packaging related products, most of the work in this space remains in the academic realm. To make seaweed polymers competitive with conventional packaging materials in terms of manufacturing costs and functionality, further research and development are required, both academically and with industry. The negative impacts of seaweed farming on marine ecology and seaweed polymers on the environment could be magnified with their development. Hence, it is also necessary to study these issues and find solutions to alleviate future issues and to avoid unseen irreversible damage to the global environment.

CRediT authorship contribution statement

Jianhua Zhang: Writing – original draft, Project administration, Conceptualization. **Marlene Cran:** Writing – original draft. **Li Gao:** Writing – review & editing. **Zongli Xie:** Writing – review & editing. **Stephen Gray:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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