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Special Series

Marine macroalgae as a feasible and complete resource to address and promote Sustainable Development Goals (SDGs)

Sara García-Poza,[1] *Diana Pacheco,*[1] *João Cotas,*[1] *João C. Marques,*[1] *Leonel Pereira,*[1] *and Ana M. M. Gonçalves*[1,2,*]

[1]*University of Coimbra, MARE—Marine and Environmental Sciences Centre, Department of Life Sciences, Calçada Martim de Freitas, Coimbra, Portugal*
[2]*Department of Biology, CESAM—Centre for Environmental and Marine Studies, University of Aveiro, Aveiro, Portugal*

EDITOR'S NOTE:

The special series addressing UN Sustainable Development Goals highlights "Environmental Management Practices Inspired by SDGs" aiming to call attention to practices, ideas, and thought-leaders contributing to sustainability in all facets of the global economy. The 2020s are a transformative decade for human interaction with the environment, largely inspired by the United Nations' 17 Sustainable Development Goals. Scientific research and environmental management practices lead the way to sustainability, and several SDGs aim to reduce our environmental footprint and preserve, protect, and restore ecological health.

Abstract

Because the world's population is increasing, science-based policies are needed to promote sustainable global development. It is important to maintain and restore the environment and help human society overcome the risks from industrialization and unsustainable exponential growth. In recent years, many studies have highlighted that macroalgae represent a key marine resource for ecological and sustainable living, thus helping to address today's global problems, such as water pollution, ocean acidification, and global warming. Macroalgae show the potential to provide innovative, ecofriendly, and nutritious food sources and natural compounds for various industries, such as biomedical, food, agricultural, and pharmaceutical industries. This review discusses how macroalgae can help us today and how they can promote a more sustainable way of life in the future. It also discusses the potential danger for ecosystems and the global population if these organisms are not part of the solution but part of the problem. *Integr Environ Assess Manag* 2022;18:1148–1161. © 2022 SETAC

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BRIEF INTRODUCTION TO 2030 AGENDA AND SUSTAINABLE DEVELOPMENT GOALS (SDGs)

The SDGs adopted by the United Nations (UN) were incorporated into the 2030 Agenda for Sustainable Development and were designed to achieve a sustainable future for the planet (United Nations, 2016). These goals seem complicated at first sight; however, they outline several social challenges and describe a viable and precise set of measures for improving interactions between society and the environment (Obura, 2020).

As the world's population increases, it becomes necessary to establish science-based policies to ensure sustainable global development. For this reason, the 2030 Agenda and SDGs recognize the importance of the issues that must be addressed globally. In recent years, climate change (SDG #13) has been approached as a problem that needs urgent mitigation measures. Improving water quality is also a priority need that SDG #6 focuses on. Both issues are caused principally by anthropogenic activities (e.g., pollution and resource overexploitation) and natural events that often lead to harmful impacts on ecosystems, public health, and economic growth. While SDG #2 aims to end hunger by reducing food waste and supporting local farms, SDG #14 aims to protect the ocean and its resources. Macroalgae can play a fundamental role in the development of efforts to comply with these SDGs.

Correspondence Ana M. M. Gonçalves, University of Coimbra, MARE—Marine and Environmental Sciences Centre, Calçada Martim de Freitas, Coimbra 3000-456, Portugal.
Email: amgoncalves@uc.pt

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MACROALGAE DESCRIPTION

Macroalgae (also called seaweed) are macroscopic marine algae that can reach several meters in length (some thalli of these algae can measure up to 65 m in length). Macroalgae are at the base of the marine food chain because they are

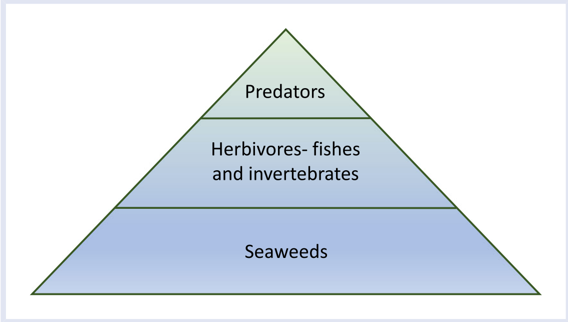

FIGURE 1 Diagram of the marine food chain based on seaweed

primary producers. In addition, they form part of a complex trophic web (Figure 1) (Butt et al., 2020; Randall et al., 2020), supporting herbivorous animal communities (invertebrates, such as some sea urchins and/or gastropods, and vertebrates, such as herbivorous fish) and providing refuge from carnivorous predators (Pereira, 2021).

Macroalgae live in seawater (or brackish water) and need enough light for photosynthesis to occur; these are the two environmental requirements that dominate their ecology. An attachment point is also important, and therefore, marine algae more frequently inhabit the coastal zone (waters close to the coast) on rocky substrates, but they also float freely (Pereira & Correia, 2015). Furthermore, macroalgae are ecologically important in aquatic systems, contributing to oxygen production, providing nursery areas to various marine animals, and serving as a food source for several herbivores (Pfister et al., 2019).

Macroalgae occupy different ecological niches. On the surface, they are moistened only with sea foam, while some species can adhere to a substrate several meters deep. In some areas, coastal macroalgal colonies can stretch out to the sea for miles. The deepest living algae are some species of red algae. Others have adapted to living in tidal pools. In this habitat, the macroalgae must withstand rapid changes in temperature and salinity and occasional drying at the rate of alternating tides (Pereira & Correia, 2015). Macroalgae live in a dynamic and multifaceted ecological habitat, and to survive in these environments, they need to be resilient to extreme and rapid fluctuations in biotic and abiotic factors. The main parameter variations that endanger macroalgal survival are temperature, pH, salinity, conductivity, light, and organic and inorganic pollutant concentrations. Even though macroalgal species adapt to conditions well, other species are more sensitive, and the drastic variation in at least one of these factors can lead to the disappearance of some macroalgal species from their habitat (Giordano et al., 2005; Kim, 2011).

More than a century has passed since the distinction of the different phyla and classes of marine macroalgae was developed based on their coloration. Macroalgae have extremely varied colors, but they all have chlorophyll (Pereira & Correia, 2015). Macroalgae are thus aquatic photosynthetic organisms (mainly marine) belonging to the Eukarya domain and to the kingdoms Plantae (green and red algae) and Chromista (brown algae). Green macroalgae are included in the phylum Chlorophyta. Macroalgal pigmentation is identical to that of vascular plants (chlorophylls a and b and carotenoids). Red macroalgae belong to the phylum Rhodophyta. They have chlorophyll *a*, phycobilins, and some carotenoids as photosynthetic pigments. Brown macroalgae belong to the phylum Ochrophyta, and all are grouped in the class Phaeophyceae; their pigments are chlorophyll *a* and *c* and carotenoids (where fucoxanthin predominates, responsible for its brownish color) (Pereira, 2021; Pereira & Correia, 2015).

In terms of morphology, the thallus (plural “thalli”) is the plant body of macroalgae. The thalli of most macroalgae species are erect, especially when submerged, unlike those of some species that are prostrate, formed by thin discs or incrustations, adhering to a substrate. The thallus of a macroalga consists of the “frond,” the erect part, which presents great variability in shape and size, and a fixation organ. These variations can be accentuated by the external environmental conditions and can be very evident in populations of the same species, as in *Chondrus crispus* and *C. crispus* var. *filiformis*, which are common in coastal regions with high wave exposure on the European shores of the North Atlantic (Pereira, 2021).

The shape or morphology of a thallus is used to differentiate the various species of macroalgae. Some algae are filamentous, and the filaments can be straight or branched. The thalli can be cartilaginous, leathery, mucilaginous, spongy, calcareous, and so forth. While some thalli have cylindrical axes, others are flattened, and others form hollow tubes. Some thalli form monostromatic or polystromatic blades or sheets (with one or more layers of cells, respectively) that are thin, generally thick, or even coriaceous; they can be orbicular or elongated, divided or not divided, and lobed or deeply divided (laciniated blades, ribbons, straps, or belts) (Pereira, 2021).

The reproduction of algae can be asexual, where fertilization does not occur, or sexual, where the fusion of gametes occurs. Normally, a single individual is capable of reproducing both asexually and sexually (Adl et al., 2005; Pereira & Correia, 2015).

The ecological value of macroalgae is also related to the fact that these organisms are naturally powerful bioaccumulators of heavy metals, noxious compounds (e.g., dibenzodioxins and other toxins), or even microplastics (Henriques et al., 2015; Seng et al., 2020). Macroalgae boost systematic marine bioremediation and carbon sequestration and neutralize ocean acidification (Gao et al., 2019). In addition, macroalgae support complex food webs in marine habitats (Figure 1) and reduce wave forces on coasts, reducing the risk of disasters in coastal areas. Moreover, macroalgae can even neutralize algal blooms by balancing the proportions of nitrate and phosphate (Trowbridge, 2014). All these characteristics make macroalgae a polyvalent and highly adaptable organism to the environment (García-Poza et al., 2020).

AIMS

Macroalgae can be considered an effective tool in working to achieve the SDGs due to their multirole action in aquatic ecosystems and society. At an ecological scale in coastal and oceanic habitats, macroalgae have a key role because they not only represent unique nursery areas with high ecological relevance but also remove inorganic pollutants, thus contributing to water bioremediation.

In this work, we examine and discuss the potential role of macroalgae in meeting the SDGs of the UN, specifically considering SDG #2 to reduce hunger, SDG #6 to improve water quality, SDG #13 to mitigate climate change, and SDG #14 to protect the ocean by considering different case studies and suggesting strategies for how this may be achieved.

THE ROLE OF MACROALGAE IN MEETING SDGs

SDG #2: Macroalgae as a resource to reduce hunger

Eradicating hunger and achieving food security remains one of the most important challenges that SDG #2 addresses. Worldwide, hunger and food insecurity have increased, while malnutrition still affects millions of children (in 2020, globally, 149.2 million children under the age of five years were stunted and 45.4 million were wasted (too thin for their height) (United Nations, 2020b; WHO, 2020).

Since ancient times, edible macroalgae have been consumed by coastal populations around the world, and records show that people collected macroalgae for food as long ago as 500 B.C. in China (Pereira, 2021). Macroalgae are still part of the usual diet in many Asian countries (China, Japan, and Korea) and popularity appears to be growing in Western cultures due both to the influx of Asian cuisine and the health benefits associated with the consumption of macroalgae (Brownlee et al., 2011). For instance, Europe consumes nearly 97 tons of seaweed each year, and the majority is imported (Love, 2018). Seaweed is mainly produced for humans, and in 2016, near 20 000 tons, mainly the species *Saccharina japonica* (formerly *Laminaria japonica*), *Undaria pinnatifida*, and *Porphyra* spp. were eaten mainly in Japan, China, and Korea (FAO, 2018).

Macroalgae have gained attention in the academic community due to their rich biochemical and compound profiles (García-Poza et al., 2020; Kim, 2011). They are eaten as a food supplement due to their nutritional profile, which is high in dietary fiber, proteins, and minerals essential to the functioning of human cell mechanisms (Leandro et al., 2020). However, due to mineral limiting factors, the recommended daily intake is only 5 g of dried biomass per day (Cotas et al., 2021).

Epidemiological evidence suggests that the regular ingestion of macroalgae can protect against a variety of modern diseases, such as obesity, diabetes, cancer, and cardiovascular diseases (Cotas et al., 2021; Leandro et al., 2020). The addition of macroalgae to food has already shown the potential to improve satiety (a seven-day daily intake of a strongly gelling sodium alginate formulation led to a significant 7% reduction (134.8 kcal) in the mean daily energy intake in healthy adults, as well as significant reductions in the mean daily intake of carbohydrates, fat, saturated fat, and protein (Paxman et al., 2008) and reduce postprandial glucose and lipid absorption rates in acute feeding studies in humans (in comparison to the control meal, 5.0 g of sodium alginate, added to food, significantly attenuated the postprandial glycemic response in type 2 diabetic individuals by 31%; Torsdottir et al., 1991). Regular consumption of macroalgae can offer a nutritionally rich addition to the diet (minerals, lipids such as polyunsaturated fatty acids, carbohydrates, proteins, and vitamins). However, micronutrient intake in excess of the reference nutrient intake could be a matter of concern, especially when bioavailability is high (Brownlee et al., 2011). High levels of minerals and dietary fibers, as well as low lipid levels, characterize many macroalgal species (Table 1).

In addition, the quality of macroalgal proteins and antioxidant activities, associated with polyphenolic compounds and pigments, makes them an interesting source of bioactive substances, especially in human and animal nutrition. Macroalgae also contain high quantities of vitamins (A, K, and B_{12}), minerals, and trace elements that are essential for the human diet (M. Barbier et al., 2019; Dawczynski et al., 2007; García-Poza et al., 2020; MacArtain et al., 2007). Thus, macroalgae have the potential to replace meat as a food product, with all the essential nutrients we need due to their high content of protein, fiber, vitamins, and minerals (Rasyid, 2017).

Small-scale farmers play a key role in food production around the world; however, they often face difficulties in accessing land and other production resources, especially in Asian countries where the major seaweed cultivation is run by farmers. In comparison to that of large-scale producers, the productivity of small-scale producers in Africa, Asia, and Latin America is consistently lower, on average, and in most countries, their income is less than half the income of their

TABLE 1 Nutritional profile of macroalgae (% of dry macroalgae) in general (adapted from Pereira, 2011)

Compound	Rhodophyta	Chlorophyta	Phaeophyceae
Lipids	0.3–3	0.3–9.8	0.1–4.5
Proteins	6.9–47	8–32	3–26
Carbohydrates (mainly polysaccharides)	43–68	33–67	30–61
Ash (mineral fraction/inorganic material)	7.8–37	7–39	9–40

larger counterparts (United Nations, 2020b). Thus, macroalgal farming may help enhance the income of small-scale farmers, thus contributing to the achievement of SDG #2. Due to the need to reduce global hunger, promoting macroalgal farming can provide new food sources (and reduce the pressure on terrestrial farmers). Linked to this need, there is the need to promote small-scale macroalgal farmers (from traditional farms) to initiate a change in developing countries.

In the majority of developing countries, most people involved in macroalgal farming are women (Msuya & Hurtado, 2017). Furthermore, successful farming practices (using low-cost materials to diminish contamination in traditional aquaculture) have increased the economic purchasing power and social empowerment of female macroalgal farmers in developing countries (Msuya, 2011). Thus, macroalgae can indeed contribute to achieving the targets and indicators proposed by the UN (Figure 2).

Macroalgae have traditionally been harvested from natural stocks or wild populations. This leads to a significant loss of wild populations due to overexploitation. Recent advances (such as the development of low-cost sustainable cultivation and aquaculture techniques or the application of 4.0 technologies in aquaculture) in marine culture techniques have led to an increase in the production of macroalgae as a true "marine culture" (Alamsjah, 2018). Therefore, efforts have been implemented to examine techniques for sustainable harvesting (hand collection of the seaweed blade to permit seaweed regeneration), for example, harvesting *Ascophyllum nodosum* and *Chondrus crispus* in Ireland from nature (Monagail et al., 2017) and developing efficient farming systems (Kim et al., 2017).

Macroalgal farming has the power to produce massive quantities of nutrient-rich (carbohydrates, proteins, lipids, vitamins, and minerals) foods for human intake, for example, *Gracilaria gracilis* cultivated in Portugal (Inácio et al., 2021) or *Ulva fenestrata* cultivated in Sweden (Steinhagen et al., 2021). Ocean farms are more sustainable than terrestrial agriculture because the cultivation of macroalgae does not require freshwater, chemical fertilizers, or arable land, which are some of the important negative factors related to terrestrial cultivation (Tiwari & Troy, 2015). Novel marine natural compound (such as pigments, polysaccharides, fatty acids, or proteins) application will potentially alleviate the dependency on terrestrial areas, allowing a more dynamic usage of soil and terrestrial ecosystems (Ferdouse et al.,

FIGURE 2 United Nations Sustainable Development Goal (SDG) #2 targets and indicators (SDG Logo Source and copyright: United Nations, https://www.un.org/sustainabledevelopment/)

2018; García-Poza et al., 2020; Holdt & Kraan, 2011; Leandro et al., 2020).

The cultivation of macroalgae is an industry that can substantially help the economy of the producing countries, providing external income and improving the socioeconomic situation of the coastal population involved (Rebours et al., 2014); of the 32.4 million tons of farmed seaweed produced globally in 2018 (FAO, 2018), some species (e.g., *Undaria pinnatifida*, *Porphyra* spp., and *Caulerpa* spp., produced in East and Southeast Asia) are produced primarily as food for humans (FAO, 2020). Furthermore, macroalgae have the potential to address hunger and ending world poverty (Figure 2), and with the appropriate management of our global macroalgal resources, we have yet another tool that can contribute to diminishing global hunger (Cornish et al., 2020).

SDG #6: Improvement of water quality by macroalgae

Access to potable water with a high water quality level is essential to guaranteeing human health and ecosystem safety. Despite global technological and economic development, many people are affected by the lack of drinking water and sanitation services. This is a relevant issue, especially currently, since the most effective method for COVID-19 prevention is handwashing. In 2017, it was estimated that 40% of the global population did not have access to a handwashing facility with soap and water in their homes. This scenario is particularly problematic in the least developed countries, where 72% of the population cannot afford what many view as a guaranteed right (United Nations, 2020a).

However, progress has been made in this area, and in fact, the proportion of the population with access to clean water and hygiene services has been rising. Nevertheless, UN SDG #6 aims to ensure that all people in the world have potable water access by 2030 (United Nations, 2020a). Macroalgae can contribute to achieving the targets and indicators proposed by the UN in relation to this goal (Figure 3).

In their natural habitats, macroalgal populations are phytoremediators. Thus, they can be used to treat contaminated waters or wastewaters from different sources with high percentages of salinity, such as estuarine and marine environments (Arumugam et al., 2018). Another proposed use of macroalgae is the utilization of macroalgal discharged residues to obtain economically valuable compounds, such as alginates or carrageenans, to develop a biofilter that can be used in salt or freshwater (Sadhukhan et al., 2019).

FIGURE 3 United Nations Sustainable Development Goal (SDG) #6 targets and indicators (SDG Logo Source and copyright: United Nations, https://www.un.org/sustainabledevelopment/)

Hence, macroalgae can be a key factor in improving water quality and decreasing water pollution. Aquatic habitats contaminated by metals are a life-threatening problem in several regions and are associated with industrialization and economic growth (anthropogenic activities). Macroalgae can accumulate metals into their cells or bioadsorb them into the cell wall and sequester these toxic substances from the surrounding environment during their growth phase, thereby detoxifying the aquatic system and allowing the ecosystem to maintain the status quo. However, these "contaminated" macroalgae need to be removed from the food chain if the heavy metal contamination levels surpass permissible limits. These limits indicate the maximum amount of heavy metals that a certain ecosystem can withstand without affecting the usual characteristics and functions of the food chain (Sadhukhan et al., 2019). In these cases, the macroalgal biomass may be valuable in the recovery of heavy or precious metals from contaminated waters.

Wild macroalgae are recognized as natural metal biosorbents; for example, brown macroalgae are known to capture lead, cadmium, copper, zinc, chromium, and cobalt from industrial effluents or wastewaters (Ortiz-Calderon et al., 2017). However, macroalgal metal uptake normally occurs through the interaction between metal ions and algal cell walls, so metal removal is not metabolically controlled (Mazur et al., 2018). Macroalgal bioremediation applications can be exploited by residues obtained from processed macroalgae (e.g., alginate extraction). This can be attractive due to the higher metal binding capacity and reusability of this type of biomass. This reusability and metal recovery from macroalgae can be achieved by desorption agents (commonly hydrochloric acid, sodium hydroxide, or calcium chloride) and deionized water to recover the adsorbed metals, promoting a circular economy (Bulgariu et al., 2015; Sun et al., 2012).

However, this use of macroalgae occurs mainly in nature with wild specimens. Currently, there are only small prototypes mainly dedicated to treating eutrophic waters, although there has been an increase in research in this field. In addition, this approach is a low-cost method that is highly efficient (Arumugam et al., 2018; Neveux et al., 2018; Valero Rodriguez, 2019).

Macroalgae are already used to increase water efficiency in industries, such as aquaculture, where macroalgae act as biofilters in an integrated multitrophic aquaculture (IMTA) system, removing the excess organic and inorganic substances from the water used to produce other organisms (i.e., fish, mollusks, and invertebrates) (Holdt & Edwards, 2014; Kang et al., 2008; Silva et al., 2015).

Table 2 shows studies and pilot-scale assays using macroalgae to bioremediate waters. As demonstrated in the table, macroalgae can be applied in various cultivation systems to clean water (mainly seawater) of excessive nutrients, heavy metals, harmful compounds, and toxins. Thus, macroalgae can be used to recover metals or compounds within a circular economy approach. If only nutrients are

TABLE 2 Macroalgae phytoremediation examples

Species	Type of contamination	Cultivation system	Benefits	Seaweed future application	Reference
Gracilaria corticata	Textile wastewater	Inshore reactor cultivation	Malachite green dye accumulation	Recover dye to be reused	Omar et al. (2018)
Ulva lactuca	Phosphating industry wastewater	Inshore reactor cultivation	Zinc removal from wastewater	Zinc recovery	Senthilkumar et al. (2019)
Gracilaria lemaneiformis	Heavy metals (cadmium, lead, and mercury) in polluted zone	Offshore aquaculture	Heavy metals removal from seawater	Mainly, phycocolloid extraction (agar)	Luo et al. (2020)
Ulva rigida	Wastewater from the biogas plant	Inshore reactor cultivation	Carbon and nutrients (ammonia and phosphate) accumulation	Manure, biorefinery	Sode et al. (2013)
Gracilariopsis longissima (as *Gracilaria verrucosa*)	Fish aquaculture wastewater (nitrite, nitrate, ammonia, and phosphate)	Inshore cultivation	Removal of nutrients from wastewater	Mainly, phycocolloid extraction (agar)	Devi and Gowri (2007)
Gracilariopsis lemaneiformis (as *Gracilaria lemaneiformis*)	Fish aquaculture wastewater (nitrogen and phosphates)	Offshore aquaculture	Reduction of nutrients in water	Various industries, for example: food and animal feed	Wei et al. (2017)

present in seawater (and not heavy metals, harmful compounds, and toxins), then macroalgae can be used as a food source due to the absence of harmful compounds. Thus, this was the origin of the IMTA aquaculture methodology, based on fish aquaculture seawater being treated by macroalgae to capture excessive nutrients from the seawater before they could be used again. The methodology is used globally (García-Poza et al., 2020). In addition, macroalgae are also utilized to remove heavy metals, and harmful compounds and toxins are discharged and burned as energy sources in power plants or used to recover compounds and metals due to their high price (Pardilhóco, Costa, et al., 2021).

Moreover, the presence or absence of macroalgae in coastal areas is a useful tool for indicating water quality and is already used in some countries in this manner (Neto et al., 2012; Wallenstein et al., 2013). For example, in Portugal, the P-MarMAT tool is used to assess the water quality along rocky shores, under the European Water Framework Directive, and permits an analysis of algal communities to characterize the water in coastal areas (Neto et al., 2012).

SDG #13: The role of macroalgae on the mitigation of the effects of climate change. The climate crisis continues to escalate as the global community shuns the full commitment needed to reverse it (United Nations, 2020b). The second warmest year on record was 2019, and this year was the end of the warmest decade (2010–2019), when massive wildfires, hurricanes, droughts, floods, and other weather-related disasters occurred around the world. Global temperatures are on track to rise to 3.2 °C by the end of the century (United Nations, 2020b). To meet the maximum temperature target increase of 1.5 °C, or even 2 °C, required by the Paris Agreement, greenhouse gas emissions must begin to decrease by 7.6% each year starting from 2020 (United Nations, 2020b).

Highly productive macroalgal species may be an important tool in the annual biological reduction of carbon dioxide and the global carbon cycle (Figure 4). Marine photosynthesis accounts for 50% of the total primary productivity of the planet (54–59 pg [a petagram = 1015 g] C $year^{-1}$ from a total of 111–117 pg C $year^{-1}$), whereas marine macrophytes (seaweeds and seagrasses) in coastal regions account for ~1 pg C $year^{-1}$ (Turan & Neori, 2010). To understand the extent of this reduction, researchers must determine the amount and speed at which this fixed carbon is recycled (Chung et al., 2013). Even though marine

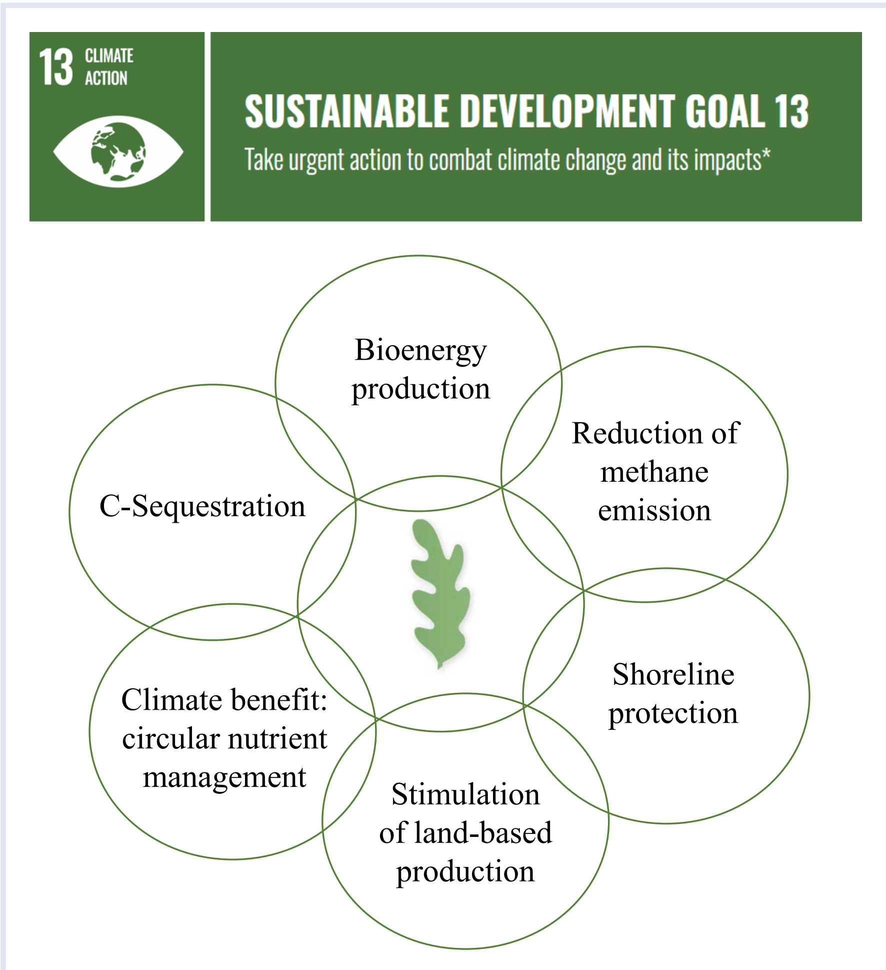

FIGURE 4 United Nations Sustainable Development Goal (SDG) #13 targets and indicators (SDG Logo Source and copyright: United Nations, https://www.un.org/sustainabledevelopment/)

macroalgal communities occupy a very small area of the coastal region (only 33%), these habitats are a key element of a strategy that combines both climate change adaptation and mitigation (Wernberg et al., 2019).

The role of oceans as carbon sinks. Biological carbon fixation is carried out by autotrophic organisms that convert released carbon dioxide into organic carbon through photosynthesis. Although marine vegetated habitats (seagrasses, marshes, macroalgae, and mangroves) cover only 0.2% of the ocean surface, they contribute to 50% of the carbon burial in marine sediments (Duarte et al., 2013). However, the potential of marine macroalgae to mitigate climate change by sequestering carbon dioxide has not yet been fully included in the emerging concept of blue carbon (Duarte et al., 2013; Nellemann et al., 2009) due to the belief that the vast majority of macroalgal production decomposes in the ocean and, therefore, does not represent a net sink of carbon dioxide. However, this viewpoint has currently been challenged (Hill et al., 2015; Moreira & Pires, 2016; Trevathan-Tackett et al., 2015) and new evidence suggests that macroalgae are a global contributor to sinkholes of oceanic carbon. A 2016 study reported a gradual increase in pH of 0.15 units and a parallel decline in pCO_2 of 100 parts per million over a 10-day period in an Arctic kelp forest over midsummer, concluding that long photoperiods in Arctic summers support sustained upregulation of pH in kelp forests, with potential benefits for calcifiers. This mechanism may increase with the projected expansion of Arctic vegetation in response to warming and the loss of sea ice (Krause-Jensen et al., 2016).

In comparison with other blue carbon sectors (mangroves, seagrasses, and marshes) that accumulate and retain large amounts of carbon in sediments, kelp forests and macroalgae beds do not have sedimentary substrates (Chung et al., 2013). Fifteen species of algae were examined to test their capacity to remove carbon, and the red algae *Pachymeniopsis lanceolata* showed the highest carbon removal rate per area of $2500–6000\,g\,C\,m^{-2}\,year^{-1}$, which is five times higher than that of tropical forests. *Undaria pinnatifida*, *Neoporphyra seriata* (formerly *Porphyra seriata*), *Saccharina japonica* (formerly *Laminaria japonica*), *Ulva australis* (formerly *Ulva pertusa)*, *Ecklonia cava* subsp. *stolonifera* (formerly *Ecklonia stolonifera*), and *Pachymeniopsis lanceolata* (formerly *Grateloupia lanceolata*) were also found to be highly efficient in removing aquatic inorganic carbon (Turan & Neori, 2010). The majority of macroalgal communities grow on hard substrates and sequester carbon, except for biomass that can be transported to the deep sea (Dierssen et al., 2009).

Climate change mitigation. The correlation between wind and storms shows that climate change will probably have an important impact on wave height and other wave parameters (Lal et al., 2012). Floods and coastal erosion are a major threat to coastal areas, and these events are already occurring, requiring the introduction of sustainable measures to address them (Duarte et al., 2013). Vegetated coastal habitats, with their capacity to provide coastal protection (E. B. Barbier et al., 2011), may help mitigate the impacts of sea-level rise and the associated increase in wave action. In addition, vegetated coastal habitats have a high capacity to produce carbonates and other materials that aid sediment accumulation, beach nutrition, and the formation of dunes on land (Hemminga & Duarte, 2000; Temmerman et al., 2004), further preventing coastal erosion (Temmerman et al., 2004). For example, great brown seaweeds (kelp) protect almost 22% of the coastline in the world, reducing sea currents and waves near the coast (Bekkby et al., 2019; Smale et al., 2013; Steneck et al., 2002; Wernberg et al., 2019). Thus, coastal erosion is reduced. Additionally, kelp that drifts ashore is important for providing nutrition to the plants and animals that inhabit coastal ecosystems while also stabilizing coastal ecosystems (Zemke-White et al., 2005). Thus, macroalgae are important for maintaining the homeostasis of the food chain and ecological services, such as nurseries, recruitment, and protected areas for various aquatic species (Roth & Marliave, 1995). Natural macroalgal niches are an essential ecological service in marine ecosystems (Bak, 2019; Hasselström et al., 2018).

Furthermore, supplementing ruminant livestock feed with macroalgae has the potential to reduce methane emissions, a possibility that, if confirmed by in vivo and on-farm experiments, could go a long way toward mitigating emissions of this powerful greenhouse gas (Duarte et al., 2017). For example, researchers have shown that including merely 0.5% of the red seaweed *Asparagopsis taxiformis* is enough to decrease methane emissions by up to 90% without affecting cow health or product quality (Black et al., 2021; Kinley et al., 2020). Additionally, prebiotic compounds and essential minerals in marine macroalgae can help improve livestock production and health (Makkar et al., 2016; Rey-Crespo et al., 2014).

Currently, we are facing a changing scenario in terms of the distribution of species due to changes in ecological parameters. For example, large brown macroalgae, such as kelp, are moving to colder waters, inhabiting the southern line of distribution occupied by temperate opportunistic macroalgal species (Álvarez-Losada et al., 2020; Diehl et al., 2020). Changes in the distribution of species in ecosystems are linked to increasing anthropogenic activity, climate change, global warming, and ocean acidification, and these factors also represent several stressors that lead to the deterioration of marine habitats where macroalgae can be a solution (Figure 4).

Blue biofuels. One way to expand blue carbon strategies to incorporate the carbon dioxide sink capacity of macroalgae is to manage macroalgal production, whether derived from aquaculture or wild populations. These approaches can include using macroalgal biomass (mainly macroalgae from the phytoremediation of pollutants and contaminants) as a biofuel that directly replaces fossil fuels (Chen et al., 2015; Kraan, 2013; Pardilhó, Costa, et al., 2021) and/or replacing food or feed production systems (which produce intense carbon dioxide emission footprints) with macroalgae-based food systems (which have much lower lifecycle CO_2 emissions) (Fry et al., 2012). Through different processes, algal biomass can be converted into different biofuels, such as biogas (by anaerobic digestion), bioethanol (through hydrolysis or fermentation), bio-oil (using the process of thermochemical conversion), and biodiesel (through oil extraction and transesterification) (Michalak, 2018). Thus, macroalgae that do not meet the standards for food, feed, and other added-value applications can be applied to biofuel production (Pardilhó, Costa, et al., 2021; Pardilhó, Cotas, et al., 2021). In this manner, the industrial competition for macroalgal biomass is reduced, and all macroalgae utilized for phytoremediation and macroalgae that drift ashore will also be exploited by the industry (Pardilhó, Costa, et al., 2021; Pardilhó, Cotas, et al., 2021). Therefore, promoting the usage of unexploited macroalgal biomass to obtain new products can be a very useful practice (e.g., the production of biofuel, bioethanol, and biogas) (Pardilhó, Costa, et al., 2021). Thus, it is desirable to reduce the pressure on macroalgae in terms of food quality.

However, novel processes are currently being developed to reduce the costs associated with the application of macroalgae as biofuels (Elshobary et al., 2020). In addition, depending on the algal biomass chemical characterization, some species are more suitable as blue biofuels (Gosch et al., 2012). For instance, a screening of selected brown, red, and green macroalgae highlighted the potential of using *Dilophus fasciola* (currently known as *Dictyota fasciola*—class Phaeophyceae) in biofuels due to its carbohydrate and lipid contents (37.97% and 4.92 dry weight, respectively) (Elshobary et al., 2020).

In addition, “blue” biofuels from macroalgae do not compete for resources with agriculture (fertilizers, herbicides, or pesticides) and are, therefore, in many aspects, more environmentally friendly than current biofuels derived from land crops (Duarte et al., 2013).

Macroalgal aquaculture as a win–win strategy. Macroalgae have an important role in shoreline protection, as well as in geochemical and biological processes in marine ecosystems (Araújo et al., 2016; Schoenrock et al., 2018). Macroalgal aquaculture can be viewed as a profitable, sustainable, and environmentally friendly solution when approached from an ecosystem perspective (Grebe et al., 2019; Zhu et al., 2020).

Many developing nations cannot afford to address climate change mitigation through high-cost solutions. Macroalgal aquaculture is a particularly robust strategy for developing coastal nations to contribute to climate change mitigation, as shown in Figure 4, while protecting their coasts and marine ecosystems from some of the effects of climate change due to the very low investment required to establish aquaculture macroalgae farms (Duarte et al., 2017).

A tactical approach to enhance the benefits of macroalgal aquaculture for climate change adaptation may be to establish macroalgal farms in areas susceptible to risk from climate change impacts, such as low-lying coastal areas that are vulnerable to flooding during storms and increasing sea level or areas prone to exposure to acidified and/or oxygen-depleted waters (Duarte et al., 2017). This approach is a win–win mitigation strategy for promoting sustainable and environmentally sound ocean-based production, such as macroalgae (Laffoley & Grimsditch, 2009).

SDG #14: How macroalgae can protect ocean resources

The conservation and sustainable use of oceans, seas, and marine resources are addressed by SDG #14. Macroalgae are an important resource that can be used to achieve the UN SDG #14 objectives (Stead, 2018), as shown in Figure 5, because they are the basis of life in the oceans. In various countries (mainly underdeveloped countries in South America, Asia, and Africa), marine strategies are divided into two parts: aquatic natural environments and economic exploitation (particularly marine biotechnology and fisheries) (Stead, 2018). Due to the lack of management and communication and distinct incompatible approaches (ecologic and economic), these two demands can have a severe impact on the conservation and sustainability of marine ecosystems and associated resources, resulting in a fragmented and dispersed approach to marine management (Stead, 2018). As demonstrated above, macroalgae can help reduce marine pollution due to their inherent capacity to accumulate metals, nutrients, and other potentially harmful compounds. Moreover, macroalgal communities also serve as nurseries for marine organisms, such as fish. For example, in comparison to seagrass beds, seaweed supports more fish juveniles in Atlantic tropical areas (Eggertsen et al., 2017).

As a result, the blue economy involves industrial marine resource exploitation from an ecological perspective to prevent or mitigate the negative impacts of marine enterprises on aquatic ecosystems (Stead, 2018). Moreover, governments must collect evidence-based data on how to improve the economic use of marine resources and how this might be accomplished by providing different types of economic assistance to ensure ecological safety while simultaneously increasing the national economy (Al-Belushi et al., 2015).

Thus, macroalgae play a significant role in both economic exploration (economic value US$ 11.7 Bn) and environmental conservation of the oceans and seas (Chopin, 2018), showing an economic value of US$ 0.35 kg^{-1} based on the biomass production of macroalgae in 35 countries according to the Food and Agriculture Organization of the UN (FAO, 2012). As a result, preserving indigenous macroalgae in their native environments is critical, as is avoiding the introduction of exotic species, which can endanger ecosystem stability. However, to promote the sustainable use of these marine resources, ecologically sustainable macroalgal production can ensure that this exploitation does not impose pressure on marine environments. Methods for growing native macroalgae have the potential to support the biodiversity of several fish, crustacean, cephalopod, and echinoderm species (Bak, 2019; Hasselström et al., 2018). The ecosystem services provided by naturally occurring macroalgal ecosystems have been evaluated to be between US$1.1 and 2.9 million km^{-2} $year^{-1}$ (Buschmann et al., 2017; Costanza et al., 2014). These macroalgal ecosystem service estimations are considered valid for extrapolations to macroalgal cultivation to appropriately determine their economic and ecological effects (Bak, 2019).

Other benefits of a blue economy model include the preservation of natural habitats and the possibility of expanding habitats into previously degraded areas. However, macroalgae may also be a barrier to UN SDG #14 in terms of conservation and maintenance of ecological status, with the increasing appearance of nonnative species and their own invasive behaviors. These factors will modify the overall ecosystem to an endangered level due to the total destruction that can occur due to invasive species. In these scenarios, macroalgae are not the actual problem but the result of anthropogenic actions and activities associated with climate change and the eutrophication of aquatic ecosystems. These ecological risks and impacts lead to various ecological and economic dilemmas for affected countries as have occurred with *Sargassum muticum* (Phaeophyceae) in various Caribbean countries, where several countries have algal blooms of this invasive species. These blooms are harmful to native species and the human population on the coast. Furthermore, this species is not exploited and discharges residues, so it goes to landfills (Sterley, 2020). To mitigate this negative impact, there is a need to develop techniques that provide benefits from invasive macroalgal species. For example, a positive economic activity gained from the reduction of endangered species biomass that ensures a sustainable future in these countries is biogas and fertilizer production (Sterley, 2020). Consequently, macroalgae are key to SDG #14 because they are the basis of ocean life, and to accomplish this goal, macroalgae need to be integrated into the strategy, as demonstrated in Figure 5.

In the future, macroalgal production could be a low-cost alternative to ease ecological pressure on food production (Stead, 2018). Because of the minimal capital investment, short crop or harvest cycle, and ease of cultivation, macroalgae can be used as an alternative source of sustenance by human coastal communities in coastal countries, giving rise to a multipurpose primary product (Sadhukhan et al., 2019). Thus, macroalgal aquaculture has the potential to alleviate

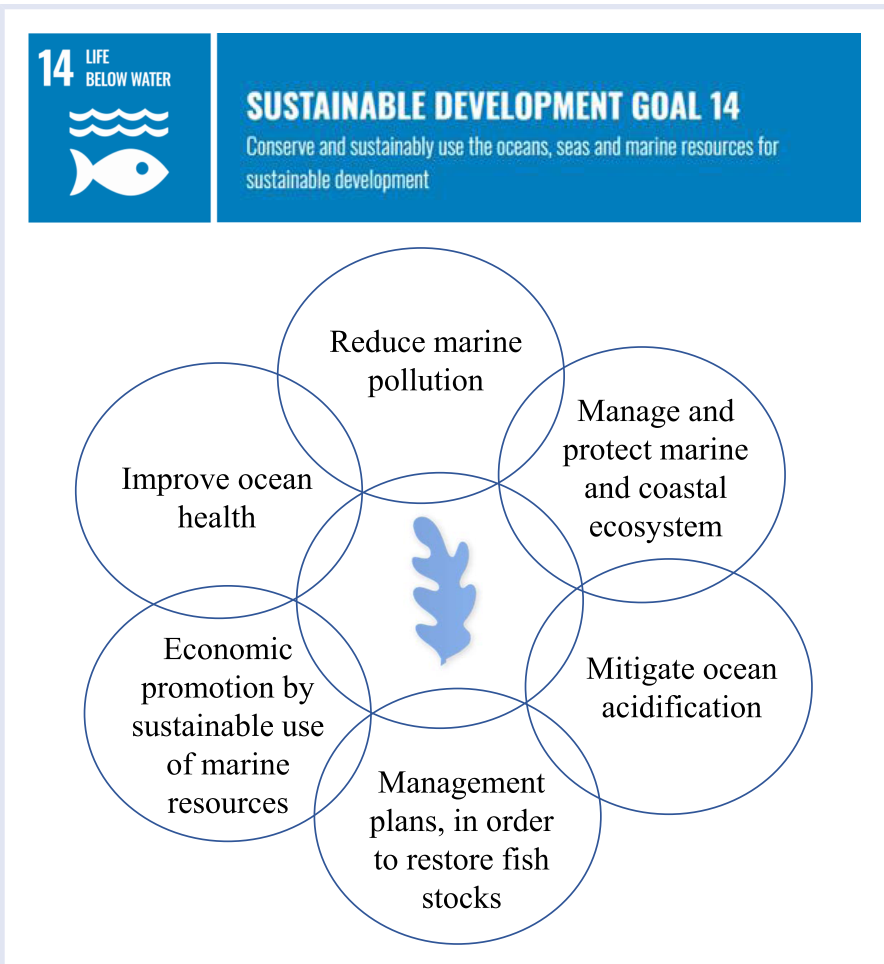

FIGURE 5 United Nations Sustainable Development Goal (SDG) #14 targets and indicators (SDG Logo Source and copyright: United Nations, https://www.un.org/sustainabledevelopment/)

climate change impacts and ocean acidification through carbon dioxide sequestration (Bak, 2019), as shown in Figure 5.

In conclusion, wild macroalgal harvesting without an ecological analysis can pose significant environmental risks, particularly when carried out for economic benefit only, as it significantly reduces primary producers, destabilizes the food chain, and takes a long time to recover (Rinde et al., 2006). Thus, macroalgal cultivation can offset negative impacts by investigating indigenous macroalgae species and reducing ecosystem eutrophication in which macroalgae are particularly effective at removing nutrients from the water, thereby controlling algal blooms (Bohlin, 2019; Pechsiri et al., 2016). In fact, certain countries harvest substantial amounts of macroalgae species; nevertheless, natural harvesting is mostly performed in sustainable ways due to the economic consequences of unmanaged harvesting in the past (Buschmann et al., 2017). Therefore, if conducted effectively, macroalgal production might be regarded as an ecological service with economic potential (Bohlin, 2019). Additionally, macroalgal aquaculture can be key to reducing overfishing and habitat degradation (Mustafa et al., 2018).

To fulfill the objectives of UN SDG #14, macroalgae may be able to contribute successfully to achieving the suggested goals. There is a need to take blue growth and the blue economy to the next level to sustainably use marine resources without jeopardizing the marine ecosystem.

SIGNIFICANCE STATEMENT AND WAYS FORWARD

Due to the wide distribution of macroalgae throughout the world, their simple cultivation, and, above all, their many nutritional and bioactive properties, these organisms represent a food alternative in underdeveloped countries, helping to reduce hunger and undernourishment throughout the world. In addition, they can be used to treat contaminated water due to their phytoremediation capacity. Although macroalgal communities occupy only a very small area of the coastal region, these habitats are key elements of a strategy that combines adaptation and mitigation of climate change, and they play an important role in the protection of marine ecosystems. An integrated technology for water resource exploration—inland, coastal, sea, and ocean—should balance the search for renewable energy and sources of food with sensitive upstream ecological requirements. Better use of inland and coastal water systems would also help improve the quality of life for impoverished communities. All these factors show that macroalgae are marine resources with the potential to help achieve the 2030 UN SDGs.

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CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest.

DISCLAIMER

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DATA AVAILABILITY STATEMENT

This is a review paper, with no data available.

ORCID

Sara García-Poza http://orcid.org/0000-0001-8519-3152
Diana Pacheco http://orcid.org/0000-0001-5509-1067
João Cotas http://orcid.org/0000-0002-5244-221X
João C. Marques http://orcid.org/0000-0001-8865-8189
Leonel Pereira http://orcid.org/0000-0002-6819-0619
Ana M. M. Gonçalves http://orcid.org/0000-0002-8611-7183

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