CHAPTER FIVE

Algae for global sustainability?

Nathalie Bourgougnon[a,*], Anne-Sophie Burlot[b], and Anne-Gaëlle Jacquin[c]

[a]Laboratoire de Biotechnologie et Chimie Marines, Université Bretagne Sud, EA3884, UBS, IUEM, Vannes, France
[b]Olmix SA • ZA du Haut du Bois, Bréhan, France
[c]The Algonauts Project, www.algonauts.org, San Francisco, CA, United States
*Corresponding author: e-mail address: nathalie.bourgougnon@univ-ubs.fr; asburlot@olmix.com; ag.jacquin@gmail.com

Contents

Advances in Botanical Research, Volume 100
ISSN 0065-2296
https://doi.org/10.1016/bs.abr.2021.01.003

Abstract

Our world has always been transforming, but even more so today with almost 7.8 billion people living on Earth. Since the beginning of the century, the world population has increased by 27%. Since 2000, Africa has shown the most significant inhabitant number increase with a positive growth rate of 65% compared to Oceania (36%) Latin America and the Caribbean (25%), Asia (24%), North America (18%) and Europe (3%) (United Nations, 2020a). Considering that our blue planet has a finite space, the role of humanity is to understand its ecosystem in order to anticipate the impact of this increase of human beings on the flora, the fauna and on the environment and in order to limit the imbalance of the ecosystem, and risk the extinction of certain species and the loss of biodiversity. In this context, in 2015, 193 countries, which are members of the United Nations Organization, adopted a universal program of sustainable development for the 2030 horizon, called the "2030 Agenda for Sustainable Development." It is focused on population numbers, the planet prosperity and on peace thanks to its partnerships. Seventeen sustainable development goals were defined. Algae (macro and microalgae) have the potential to respond to some of the world's most pressing challenges. In this chapter, the sustainable development goals will be approached by proposing solutions based on algae and on key players who utilize them in a healthy functioning of the global ecosystem. We propose a vision of a responsible seaweed industry, playing a globally significant role in food security, climate change mitigation, and supporting the marine ecosystem, as well as contributing to job-creation and economic growth. This chapter is a follow up of volume 71 sea plants and volume 95 seaweeds around the world: State of art and perspectives.

1. Introduction

The Oceans are the world's largest ecosystem, covering more than 70% of the earth's surface and they support floating forests with animals and sea plants. Microalgae and macroalgae are important marine resources playing a major role in supporting the rich biodiversity of the ocean. They constitute primary producers in the ecosystems at the base of the marine food chain, are food for many invertebrates and fish and support for detritus feeders and decomposers. Macroalgae or seaweeds form the most extensive and productive benthic marine vegetated habitats. Along the global coastlines of the oceans (intertidal rocky shores, coral reefs or seagrass meadows), its habitat was estimated to cover about 3.4 million km^2 and support a global net primary production of oxygen emissions of about 1.5 PgC $year^{-1}$ (Krause-Jensen et al., 2018). These ecosystems also provide nursery grounds, coastline protection from erosion and nutrient fixation (Gattuso et al., 2006; Keith, Kerswell, & Connolly, 2014).

The use of macroalgae dates back to Shen Nung, the father of husbandry and medicine, in approximately 3000 BC. Seaweeds were reported to be utilized in Iceland in 960 BC. The *Chinese Book of Poetry* (800–600 BC) praised housewives for cooking with algae, and the *Chinese Materia Medica* (600 BC) refers to algae as follows: "*Some algae are a delicacy fit for the most honorable guest, even for the King himself*" (Levine, 2016; Pérez-Lloréns, Mouritsen, Rhatigan, Cornish, & Critchley, 2020).

Seaweeds were seen as a fundamental component of the Ocean as well as the beings associated with it, they also held an essential connection to the land and the people who dwelt there (Pérez-Lloréns et al., 2020). For many centuries, coastal populations have harvested a wide variety of seaweeds within all algal clades: red (*Rhodophyta*), brown (*Phaeophyceae*), and green (*Chlorophyta*). They were most often first used for domestic purposes, such as for human consumption as vegetables in salads, soups, and main dishes, including sushi and as flavorings in chips and snacks. The industrial and commercial use of algae was marked successively in the 17th century by the production of glass and soap (France and Norway). Since the 19th century macroalgal biotechnology has included the production of iodine and phycocolloids (alginate, agar-agar, carrageenan) from *Phaeophycea* and *Rhodophyta*.

Because of their biodiversity and expansion in various living environments, these organisms contain many interesting metabolites for the production of horticultural, cosmetics, and animal welfare products (Fleurence & Levine, 2016; Leandro, Pereira, & Gonçalves, 2020; Levine & Fleurence, 2018). At present, the main directions in algal biotechnology are biofuels, agricultural biostimulants for crop plants, probiotics for aquaculture, wastewater treatment, and biomedical applications of extracted compounds (pigments, polyphenols, polysaccharides) (Leandro et al., 2020).

In 2013, the value of the global harvest of seaweeds was estimated at US$6.7 billion, and over 95% was produced in aquaculture, with China and Indonesia being the top producers (FAO, 2015). In addition to macroalgae, some microalgae are cultivated for food and food additives (FAO, 2016). The annual macroalgae harvest from wild and cultivated crops was 28.4 million tons in 2014 (FAO, 2016), destined for human consumption and the production of hydrocolloids used as thickening agents in foods and beverages. As their promising interest, cultivation and applications increase, their value in the market rises too. It is estimated that in 2025 this value will exceed the figure achieved in 2019 by twofold (Fig. 1).

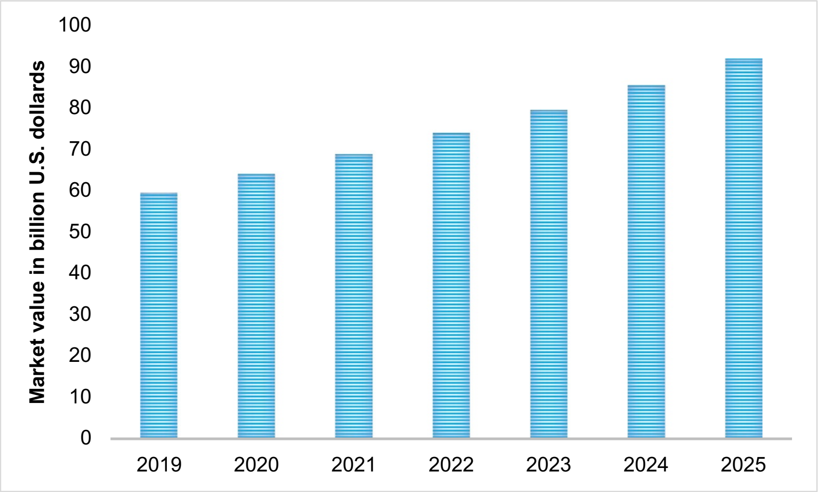

Fig. 1 Value of the seaweed market worldwide from 2019 to 2025 (in billion US dollars)—https://www.statista.com/statistics/603851/value-commercial-seaweed-market-worldwide/.

In 2015, 193 countries came together to put out a plan to improve the planet's health. At a time of global climate change we are faced with record high temperatures; cold episodes in Europe, the disruption of the Gulf Stream, the multiplication of forest fires, the migration of populations, the increase in threatened populations, the migrations of populations into coastal areas, or the resurgence of diseases and the reduction of biodiversity. These countries made a list of 17 sustainable development goals (SDG) to achieve a better and more sustainable future for all. They addressed the global challenges we face, including those related to poverty, inequality, climate change, environmental degradation, peace and justice. The 17 goals are all interconnected, and in order to leave none behind, it is important that we achieve them all by 2030.[a] Some institutions, NGO's, associations, companies, research laboratories, participatory science, as well as international and European projects are involved around Ocean challenges and support these initiatives. For example, the Intergovernmental Oceanographic Commission of UNESCO[b] proposes an ambitious program: The United Nations Decade

[a] https://www.un.org/sustainabledevelopment/sustainable-development-goals/

[b] https://en.unesco.org/

of Ocean Science for Sustainable Development (2021–2030). The European Marine Board[c] (EMB) the leading European think tank in marine science policy provides a platform to advance marine research and to bridge the gap between science and policy in order to meet future marine science challenges and opportunities.

The ocean is intrinsically linked to many of the global challenges facing the world, including climate change, food and water security and health. In this context, we propose to explore the biological, biotechnological, ecological, societal and economic solutions to climate issues that algae might contribute to, to make our planet feel great again, paraphrasing a favorite Donald trump citation who is apparently interested in making only the USA great again.

2. Algae, a long history

The term "algae" designates predominantly aquatic photosynthetic eukaryotes chlorophyll "a"-containing what stretches from unicells of a few microns in diameter, to complex multicellular forms such as the giant kelps that can reach more than 30 m in length (de Reviers, 2003). Most algae are photosynthetic organisms that acquired the trait some 1.8 billion years ago after an unknown non-photosynthetic unicellular eukaryote engulfed, or was invaded by a photosynthetic cyanobacterium close to *Gloeomargarita*. This event ultimately resulted in a cell containing a photosynthetic plastid surrounded by two membranes with a highly reduced cyanobacterially derived genome. This event, known as the primary endosymbiosis, gave rise to the extant *Archaeplastida*, which includes the *Glaucophyta*, *Rhodophyta* (red algae) and *Chloroplastida* (green algae and land plants) (Tirichine & Bowler, 2011). Brown algae have had a very different evolutionary history, as they have acquired the ability to achieve photosynthesis through a secondary endosymbiosis event. The other lines such as Cryptophytes, Haptophytes, Golden Brown Algae and Dinophytes, are therefore eukaryotes with no direct relationship with terrestrial plants. The lines resulting from secondary or even tertiary endosymbiosis between a primitive non-photosynthetic eukaryote and unicellular red algae include the Ochrophytes within Stramenopiles, Cryptophytes and Haptophytes lines.

[c] https://www.marineboard.eu/

Derived from endosymbiosis with a green unicellular alga, the lines are grouped within Euglenophyceae and Rhizaria (Niklas & Kutschera, 2010). Such events involved a second heterotrophic eukaryote that engulfed not a *cyanobacterium* but a green or red photosynthetic eukaryote and resulted in plastids with three or four membranes around them. Both the primary and secondary endosymbiosis caused massive losses of genes from the engulfed genome, many of which have been transferred to the host genome. This process of endosymbiosis gene transfer has contributed widely to the evolution of algae (Adl et al., 2012; Boudouresque, 2015; Brown et al., 2013; Burki et al., 2016; Leliaert et al., 2012; Tirichine & Bowler, 2011).

3. Sustainable development goals and algae-based solutions

3.1 No poverty: End poverty in all its forms everywhere (Goal 1)

End poverty in all its forms everywhere is the first sustainable development objective of the 2030 Agenda. According to the United Nations, more than 700 million people, 10% of the world's population, still live in extreme poverty. Consequences of poverty for the populations are the lack of the most basic needs like food supply, health, education, access to water, to electricity and sanitation. Its causes include unemployment, social exclusion, and high vulnerability of certain populations to disasters, diseases and other phenomena which prevent them from being productive (United Nations, 2020a, 2020b). The majority of people living on less than the poverty headcount ratio of USD 1.90 a day, fixed by the World Bank, live in Sub-Saharan Africa (Fig. 2).

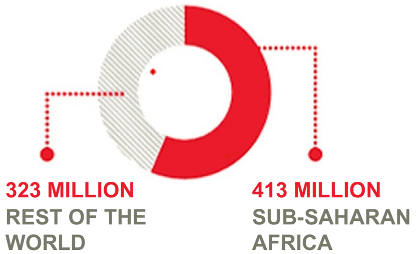

Fig. 2 736 million people lived in extreme poverty in 2015, 413 million in Sub-Saharan Africa (United Nations, 2020a).

Poverty affects populations, prosperity and peace. SDG number one is linked with all the other SDGs. Algae can bring solutions to the causes and also to the consequences of poverty (Fig. 3).

To limit poverty, its causes have to be avoided. Besides algae providing food (see Sustainable Development Goal 2), they can also provide clean water (see SDG 6), green energy (see SDG 7) improve health (SDG 3), they also represent a biomass for people:

1. to work, to liberate themselves and to flourish personally,
2. to have social interactions, health and social protection, security and,
3. to be less vulnerable in case of environmental disasters and diseases.

For coastal countries, fishery is usually the main economic activity, surpassing all other agricultural activities. Fishing escalates on a daily basis due to the involvement of a heavily populated coastal community. However, such operations are becoming more unsustainable with destructive fishing practices coupled with illegal fishery issues and communal clashes. In order to create a sustainable coastal community, especially at geographically isolated, marginalized, and vulnerable locations, the creation of alternative or sustainable livelihood options capable of unlocking the potential of the oceans seems vital. In this way, seaweed production and their use are becoming increasingly attractive to coastal communities for their socio-economic and environmental effects. Depending on seaweed cultivation and harvesting seasons, adjustments of the fishing industries can be made and offer a new and supplementary revenue. A study led in Sri Lanka has concluded that seaweed farming is reasonably profitable and generates considerable additional employment opportunities, thus is a financially profitable venture. The economic viability indicators, estimated for an average of 25 seaweed rafts, have shown an annual net income including moderate cash returns for an investment of USD 253 and a benefit-cost ratio (BCR) equal to 1.19 (Ginigaddara & Lankapura, 2018). The technology for seaweed harvesting both from the wild and farmed is relatively simple and requires low initial capital investment. The crop can be harvested in about 6 weeks and it can be dried on mats, grass, or on the sand on the beach. Seaweed farming is a system that can be replicated in other potential locations in the world. In South America, or in Brazil for example, seaweed farming is also identified as a significant source of income for individual households. Beyond the favorable economic effects on individual farm families, seaweed cultivation has extended beneficial effects to the entire economy of certain countries. For instance, it has contributed significantly to the economy of the Zanzibar Islands of Tanzania by becoming a leading foreign exchange earner that accounts for more than 90% of

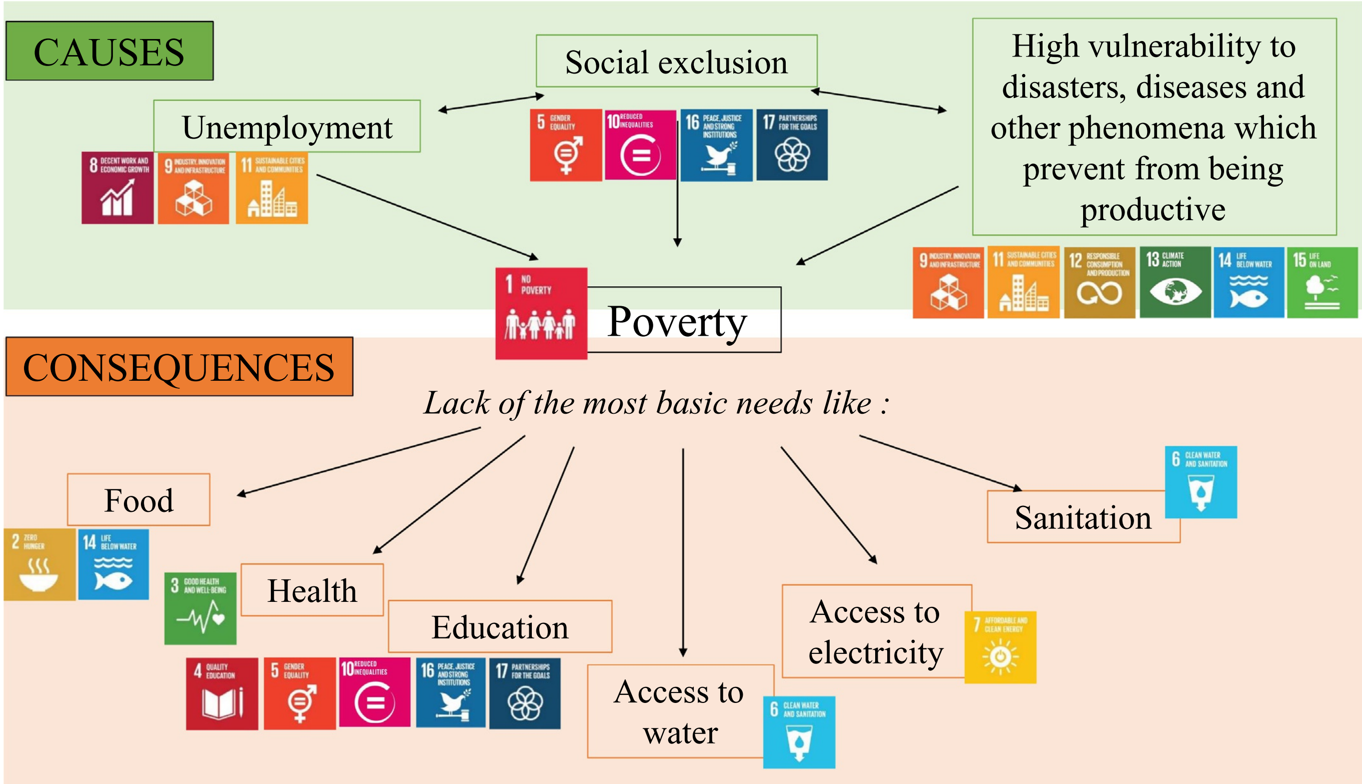

Fig. 3 Poverty affects populations, prosperity and peace. Sustainable Development Goal (SDG) number one is linked with all the other SDGs. Algae can bring solutions to the causes and also to the consequences of poverty.

Zanzibar's marine export products (Rebours et al., 2014). Nevertheless, sometimes, having a job does not guarantee a decent living. In fact, 8% of the employed workers and their families worldwide lived in extreme poverty in 2018 (United Nations, 2020a). To decrease this percentage, solutions exist. As previously mentioned, the production and transformation of algae can represent a supplementary revenue. While fishing, fishermen can also harvest or cultivate seaweeds and then sell them both. Furthermore, the development of integrated multitrophic aquaculture (IMTA) is being increasingly considered. Land based and nearshore aquaculture systems which combine fed aquaculture species (e.g. finfish), with inorganic extractive aquaculture species (e.g. seaweeds) and organic extractive species (e.g. suspension and deposit-feeders) cultivated in proximity are both systems described as IMTA. These systems should significantly increase the sustainability of aquaculture, based on a number of potential economic, societal and environmental benefits, including the recycling of waste nutrients from higher trophic-level species into the production of lower trophic-level crops with commercial value. Today, some marine IMTA systems, primarily in Asia (China), have been commercially successful at an industrial scale, while experimental projects are now scaling up toward commercialization in Canada, Chile, the USA and in some European countries. Another example is the villagers in the peninsula of Placencia in Belize, in Central America. During the sunny season, they work for the tourism industry and later in the low seasons they turn to the sea and its bountiful provision of seafood (Placencia Seaweed Farmers, 2016).

As the farming areas are generally in intertidal zones, men and women can safely access the seaweed plots. These factors allow women, in particular, an important opportunity to earn some income for themselves and their families while men work as fishermen and in other sectors. In the study of Ginigaddara et al., the employment generation of seaweed farming in the study area, in Sri Lanka, has been estimated at 3392 man days (1280 man days plus 2112 woman days) per annum. The employment potential of seaweed farming, especially as a means of female employment has been proved (Ginigaddara & Lankapura, 2018; Rebours et al., 2014). Several studies have also mentioned that women tend to be more patient and more willing to learn about sustainably managing local seaweed resources. This trend is seen in every region, particularly in Asia (China, India Indonesia, Malaysia, the Philippines) and in Africa (Ghana, Morocco, Zanzibar) (FAO, 2018; Msuya & Hurtado, 2017).

By 2030, the first objective of "No poverty" is to build up the resilience of the poor and those in vulnerable situations and reduce their exposure and vulnerability to climate-related extreme events and other economic, social and environmental shocks and disasters. This objective is to ensure the significant mobilization of resources from a variety of sources, including through enhanced development cooperation. This in order to provide adequate and predictable means for developing countries, in particular the least developed countries and to implement programs and policies to end poverty in all its dimensions. A remarkable example of sustainable development success and of international cooperation is the Red Seaweed Promise™, a program launched by the international company Cargill, that produces colloids to help ensure a long-term sustainable red seaweed supply chain. The program is specifically designed to address key sustainability challenges for the harvesting and cultivation of red seaweed, while enhancing producer livelihoods, supporting local communities and conserving the marine environment. Red seaweed is the raw material needed to produce carrageenan, a texturizer used in various applications such as dairy, confectionary and personal care products. The program also answers food industry and consumers' needs for more sustainable food ingredients, with a commitment to sourcing 60% of sustainable red seaweed by 2025. Cargill utilizes red seaweeds from four continents (South America, Asia, Africa and Europe). Furthermore, for this kind of project or program to work well and to be beneficial for both providers and users of genetic resources like algae, the Nagoya Protocol was adopted in 2010 during the 10th meeting of the Conference of the Parties to the Convention on Biological Diversity (COP 10) of United Nations, in Nagoya, Japan. It became implemented in 2014. Its objective is the fair and equitable sharing of benefits arising from the utilization of genetic resources, thereby contributing to the conservation and sustainable use of biodiversity. By helping to ensure benefit-sharing, the Nagoya Protocol creates incentives to conserve and sustainably use genetic resources, and therefore enhances the contribution of biodiversity to development and human well-being (Convention on Biological Diversity, 2015). The GlobalSeaweed STAR program has accomplished the creation of sound policy frameworks applied to the seaweed industry at national, regional and international levels, based on pro-poor and gender-sensitive development strategies, and supports accelerated investment in poverty eradication actions. It is funded to improve the seaweed industry, the fastest-growing of all aquaculture sectors, with an annual growth rate of 10% and a value in excess of USD 5 billion. The main challenges are to prevent the vulnerability of crops to disease outbreaks and pest infestation and to fill the lack of biosecurity measures and legislation governing the movement of seaweeds between regions and continents. The key ecological and socio-economic challenges preventing the sustainable economic growth of this industry were identified in a United Nation University (UNU) Policy Brief led by Dr Elizabeth Cottier-Cook from the Scottish Association for Marine Science (Cottier-Cook et al., 2016). In some cases, operations in the seaweed industry can have a negative impact on the environment and therefore they can increase the vulnerability of certain populations to disasters, diseases and other phenomena which prevent them from being productive. For example, harvesting of wild brown seaweed *Laminaria hyperborea*, using specifically designed trawling equipment, remains somewhat controversial as the removal of, and interference with natural habitats (specifically kelp forests) has the potential to affect local biodiversity and ecosystem integrity, and may contribute to coastal erosion (Stévant, Rebours, & Chapman, 2017). Nevertheless, projects like the SLAMIR project led by a natural park in Brittany, France are in partnership with national research centers and French companies' union working on seaweeds. They exist to facilitate access to data on kelp forests to maintain their ecophysiology and to sustainably manage their exploitation (Parc Naturel Marin Iroise, 2018).

Though major constraints, such as unfavorable weather and uncertain market conditions have negatively affected the progression of seaweed cultivation, many countries have illustrated the potential of seaweed farming as a profitable commercial enterprise adding opportunities for added value, integration, and earning much needed foreign exchange through exporting as well as for local development (Rebours et al., 2014). Before starting a new seaweed farm, it is essential to know that poor quality of planting materials, distortions in the market, improper aquatic environments, and poor post-harvest handling have been identified as major constraints. This is why it is important to protect our environment through understanding its serviceability. In several countries around the world, the perceived importance of algae as a vital livelihood option has proved that the system is socially and economically acceptable among coastal communities. Seaweeds have already been identified as a catalyst of social progression in coastal communities, providing substantial income while rendering extensive employment opportunities to the farming households.

3.2 Zero hunger: End hunger, achieve food security and improved nutrition and promote sustainable agriculture (Goal 2)

An estimated 821 million people were undernourished in 2017. The prevalence of undernourishment has remained virtually unchanged in the past 3 years at a level slightly below 11%. This progress sends a clear warning that more must be done, and urgently if the Sustainable Development Goal of Zero Hunger is to be achieved by 2030. The global demand for meat from livestock (excluding fish) is projected to increase from approximately 313 million tons in 2014–2016 to 455 million tons by 2050, along with a projected increase in the global demand for plant protein (i.e. vegetable and forage) for the production of livestock feed (Magnussona et al., 2019). Animal proteins come at a very high environmental cost. The largest agricultural global greenhouse gas contribution is from cattle and sheep production systems that are responsible for up to 18% of total global greenhouse gas emissions and are mainly in the form of enteric methane. These animal production systems also require more arable land (factor of deforestation) (Herrero & Thornton, 2013; Kinley et al., 2020). Population growth is driving the need to find new protein and fiber sources to feed future populations and fight food insecurity. Algae are traditionally consumed as sea vegetables in Asian countries. In Japan, the daily amount of seaweed eaten is estimated at about 4–8 g per capita (dry weight). The main species used as food are two brown seaweeds, kombu (*Laminaria japonica*) and wakame (*Undaria pinnatifida*) and the red seaweeds nori (*Porphyra/Pyropia tenera*, *Porphyra/Pyropia yezoensis*). In Europe, seaweeds are not considered as traditional foods. However, in 1990 the French National Academy of Medicine and the High Council for Public Hygiene authorized the use of 26 species of seaweeds in human food as sea vegetables. Algae are frequently sold in organic and health food shops. Marine algae contain significant quantities of vitamins, minerals, dietary fibers, proteins, polysaccharides, and various micro- and macroelements (Fig. 4). Seaweeds contain a wide diversity of minerals and trace elements: sodium, calcium, chlorine, magnesium, zinc,

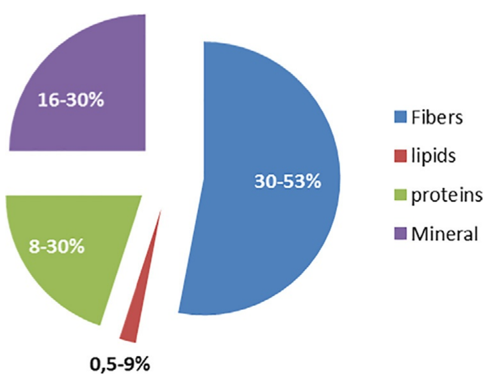

Fig. 4 Global composition of seaweed.

copper (i.e., *Palmaria palmata*, *Fucus vesiculosus*, *Laminaria* sp.). These compounds are directly implicated in the development, growth, or reproduction conditions to perform physiological functions. Nutrient contents can vary with species, geographical location, season, temperature, culture conditions and processes or biomass storage (Wells et al., 2017).

The protein content is generally high in algae, especially in red algae where it can account for up to 47% of the dry matter (red algae such as *Pyropia tenera*) (Harnedy & FitzGerald, 2011; MacArtain, Gill, Brooks, Campbell, & Rowland, 2007; Rupérez, 2002; Wells et al., 2017). Algal proteins are of importance as a source of dietary protein, essential amino acids, as well as for the bioactive potentials of specific lectins, enzymes and protein derivatives such as peptides (Stengel, Connan, & Popper, 2011). Some examples of red and green seaweeds *Pyropia* spp. (nori), *Palmaria palmata* (dulse), *Ulva ohnoi* (sea lettuce) often contain high levels of protein (Table 1). The Spirulina (Cyanobacterium *Arthrospira platensis*) and various commercial species of the unicellular *Chlorella vulgaris* (Chlorophyta) contain up to 70% dry weight protein. Proteins extracted from seaweeds have a high degree of *in vitro* digestibility. These algae also have an amino acid profile that compares well with eggs, notably containing all of the essential amino acids (EAA) that humans cannot synthesize and must obtain from foods (Fleurence &

Table 1 Main seaweeds used as foods in Japan and in Europe.

Species	Japanese name	European name	Food use
Monostroma, *Enteromorpha*, *Ulva*	Aonori	Aonori Sea lettuce	Dried powder for cooking preparation
Porphyra tenera	Nori		Dried ingredients (makis)
Porphyra yezoensis			Salted salads
Gracilaria	Ogonori		Salted salads
Grateloupia filicina	Mukadenori		
Palmaria palmata	Dulse	Dulse	Dried ingredients
Ecklonia cava	Arame		Dried boiled with sauce
Undaria pinnatifida	Wakame	Wakame	Dried or salted soups, salads
Laminaria japonica	Kombu		Dried or salted soups, boiled with sauce
Hizikia fusiformis	Hiziki		
Laminaria digitata			Dried
Himanthalia elongata		Kombu	Dried or salted soups, salads
		Sea spaghetti	Dried Boiled with sauce

Levine, 2016). Aspartic and glutamic acids constitute a large part of the amino acid composition of these seaweed proteins and are responsible for the special flavor. Original hydrocolloids (alginates, carrageenan, agars) are the main additives used by the food industry in many dairy products (e.g. yogurts, flavored milkshakes, flans, jellies, ice creams, and beers) and meat products (e.g. hams), as a thickening, emulsifier or stabilizing agent. Agars could be a vegetarian substitute for gelatine. Lipids and more particularly polyunsaturated fatty acids, sterols, vitamins such as vitamins C or B12 with antioxidant properties are also present in macroalgae (Holdt & Kraan, 2011). Consequently, algae are low-calorie foods and already commercialized under multiple brands, and labeled with "fat-free," "gluten-free," "mineral rich" or "low in carbohydrates." Algae represent natural and healthier substitutes to pasta or to bacon (i.e. *Himanthalia elongata*, as spaghetti, and *Palmaria palmata*, as sea bacon). Other algae are used as food items such as the well-known nori sheets (*Pyropia*) used to prepare sushi rolls or crispy thin snacks. There are many other recipes such as wraps with *Undaria pinnatifida* (wakame) and *H. elongata*, or laverbread, a paste prepared with boiled nori (also recognized as laver) and in desserts such as innovative Spanish Turróns with crushed nori algae (Leandro et al., 2020) (Fig. 5).

The rise of TV cooking shows, blogs and online recipes hosted by several renowned creative chefs in different countries, has increased new food trends and encourage the consumption of algae. There are also trends for: eating less meat, eating a vegan diet and eating less dairy products in favor of vegetable proteins, with growing concerns about all aspects of sustainable and clean food production and "snacking" (Rioux, Beaulieu, & Turgeon, 2017). With these changes in attitude, the integration of algae as an alternative source in the daily diet has a great potential.

3.3 Good health and well-being: Ensure healthy lives and promote well-being for all at all ages (Goal 3)

Ensuring healthy lives and promoting well-being at all ages is essential for sustainable development. Before the COVID-19 pandemic, major progress was being made in improving the health of millions of people. Significant strides had been made in increasing life expectancy and reducing some of the common killers associated with child and maternal mortality. But more efforts are needed to fully eradicate a wide range of diseases and to address many different persisting and emerging health issues.

Back in the 1750s, doctors observed that being near the Ocean appeared to have a positive effect on human health. This thought was later scientifically

Fig. 5 Sea bacon by Seamore food company (https://www.seamorefood.com/)—Pasta by MorbiAlgues (© Nathalie Bourgougnon)—Nougat Alga Nori by Vincens (https://www.vicens.com).

proven, concluding that living (or being) next to the Ocean entailed many health benefits. Even today, foods are not only to satisfy hunger and to provide necessary nutrients but also to improve the physical and mental welfare of consumers and to prevent nutrition related diseases such as cardiovascular disease and osteoporosis (Hamed, Özogul, Özogul, & Regenstein, 2015; Levine, 2016). In addition to their nutritional value, algae are thus increasingly being marketed as "functional foods" or "nutraceuticals." These terms have no legal status in many nations but describe foods that contain bioactive compounds, or phytochemicals, that may benefit health beyond the role of basic nutrition (Holdt & Kraan, 2011; Wells et al., 2017). Indeed, seaweeds have developed effective mechanisms to survive many biotic threats, like bacteria, virus, or fungal infections. Because they are sessile organisms, seaweeds have evolved to live in variable, extreme, and hostile abiotic environmental and stressful conditions, tolerating temperature changes, salinity, environmental pollutants, or UV radiation exposure (Lalegerie, Gager, Stiger-Pouvreau, & Connan, 2020). These conditions cause these seaweeds to be able to produce a wide range of compounds called "secondary metabolites," like pigments, vitamins, phenolic compounds, sterols, polysaccharides, other bioactive agents and some extremely relevant biochemical mechanisms with biomedical applications (Fleurence & Levine, 2016; Ioannou & Roussis, 2009; Kornprobst, 2005).

These compounds relate to a vast spectrum of biological activities such as antibacterial, antifungal, antiprotozoal, anticoagulant, antithrombotic, or antiviral activities (Cardozo et al., 2007; Déléris, Nazih, & Bard, 2016; El Gamal, 2010; Schaeffer & Krylov, 2000). Fibers can increase feelings of satiety and aid the digestive transit through their bulking capacity and therefore may be present in sufficient amounts when included in the diet to prevent metabolic syndrome associated with obesity, type 2 diabetes, and cardiovascular diseases (Jakobsdottir, Nyman, & Fak, 2014). Epidemiological evidence comparing Japanese and Western diets have correlated seaweed consumption (5.3 g/day in Japan) with a decreased incidence of chronic disease (De Jesus Raposo, de Morais, & de Morais, 2016). In 2020, Cherry et al. (2019) provided an innovative approach to consider how the gut microbiota may utilize seaweed phytochemicals, such as polyphenols, polyunsaturated fatty acids, and carotenoids. They provided an updated discussion regarding the catabolism of seaweed-derived complex polysaccharides with potential prebiotic activity. As suggested by Cian, Drago, de Medina, and Martinez-Augustin (2015), algal proteins and carbohydrates that escape complete digestion in the small intestine may benefit humans by stimulating an immune response indirectly via the promotion of microbial responses. Dietary modulation of the colonic flora and the impact of bacterial fermentation products on human health are rapidly evolving areas of research and are likely to be especially important considerations in assessing the health benefits of algal-derived foods (Wells et al., 2017).

In the literature, sulfated polysaccharides rich in alginate, fucose, carrageenan and carotenoid are always cited to be seaweed's most important active metabolites as potential chemotherapeutic or prebiotic/chemo preventive agents. Two examples of sulfated polysaccharide antiviral properties against anti-HIV are respectively the gel named Carraguard used as vaginal microbicide that blocks HIV and other STD (Sexually Transmitted Diseases) or the nasal or throat spray Carragelose® used against respiratory viruses (Fig. 6).

In the presence of calcium, alginates form an irreversible matrix well adapted for tissue engineering, as entrapment and/or a delivery vector of

Fig. 6 Example of commercial products. Carragelose® marinomed (https://www.carragelose.com/en).

a variety of drugs and for use in cell, bacteria, fungi or enzyme entrapment. These biomaterials are known to be biocompatible, nonedible, and immunogenic. Alginates can be use as composite materials to elaborate hemostatic wound dressings. AlgiDERM and Sorbsan are calcium alginate dressings made of sterile purified alginate fibers. Up to 20 times their weight of exudate is absorbed into a web-like gel. They are easily removed without damaging healthy tissues (Rinaudo, 2008). A hydroxyapatite putty or self-curing resin was made by mixing sodium alginate in a non-decay-type fast-setting calcium phosphate cement, which could be very useful for certain surgical procedures. This hydroxyapatite/alginate mixture is potentially a valuable new biomaterial for use in plastic and reconstructive surgery, as well as in oral and maxillofacial surgery. Alginate also offers a mucoadhesive property which could serve as a potential advantage in mucosal drug delivery through conjugation by the formation of covalent bonds with thiol-bearing compounds (Kassem et al., 2015). These authors conjugated sodium alginate with thioglycolic acid to increase the mucoadhesive potential of resveratrol (a polyphenolic phytoalexin) microspheres. This complex shows a promising therapeutic efficiency toward the treatment of periodontal disease in vitro. In fact, resveratrol was reported to possess significant antimicrobial properties on periodontal pathogens in vitro and to stimulate osteoblastic differentiation and bone formation in vitro. However, the therapeutic applications of this drug are strongly limited because of its poor oral bioavailability due to rapid metabolism in the liver together with the entero-hepatic cycle. Clinical evaluation is still in progress (Kassem et al., 2015).

Non-polar or neutral lipids are an important lipid class in seaweeds known to include molecules with attractive bioactivities such as sterols, hydrocarbons, and carotenoids. Phytosterols have been reported to be efficient in cardiovascular diseases and as anti-inflammatory agents. Fucoxanthin, a carotenoid derivative found in brown seaweeds, is known for its anti-obesity effect and the ability to reduce blood glucose and plasma insulin levels (Terme, Chénais, Fournière, Bourgougnon, & Bedoux, 2019). Fucoxanthin and its deacetylated metabolite also exhibit antiproliferative and cancer-preventing influences (Déléris et al., 2016). Phlorotannins have been extensively investigated for various biological activities such as antioxidant, anticancer, anti-inflammatory, anti-allergic, antidiabetic, antihypertensive, and neuroprotective effects (Thomas & Kim, 2011). The anti-dyslipidemia activity of dieckol extracted from brown seaweeds *Eisenia*, *Ecklonia*, and *Ishige* genera must be highlighted because it was more effective than lovastatin in an in vivo model. The lectin griffthsin, first isolated from aqueous extracts of *Griffthsia* sp. showed excellent antiviral (Japanese encephalitis virus, SARs-) results over a variety of animal models and will probably move into clinical trials soon (Rosa et al., 2019).

In the pursuit of our well-being, marine cosmetics are also an economic reality in France, the USA or Brazil (Couteau & Coiffard, 2016; Wang, Chen, Huynh, & Chang, 2015). The global beauty market stated that the cosmetics industry will continue to develop due to the growth of the middle class in many developing countries. The advantages of natural ingredients are their environmental friendliness, fewer side effects, and safe use (Jesumani, Du, Pei, Aslam, & Huang, 2020). Cosmetic products not only have to comply with strict rules concerning the use of chemical substances (EU regulation No. 1223/2009 on cosmetic products) but must also satisfy consumer demands for products containing effective natural and non-toxic ingredients. Seaweed is used as a plant extract and there are no restrictions for cosmetic use (Bedoux, Hardouin, Burlot, & Bourgougnon, 2014). The main classes of actives in cosmetic care products are used for anti-aging care, anti-photoaging, slimming care, photoprotection, moisturizing and skin-whitening. Seaweed is of interest, because it contains active molecules also for cosmetics. In addition, the production of these molecules can be optimized: by selecting a season when the algae synthesize a lot of these compounds, by setting culture conditions that promote the production of these active molecules by the algae, and by developing a transformation process which isolates them by eliminating the others. It is therefore concentrated. HELIONORI® (Gelyma, France) supplies natural skin UVA protection against sun burn that burns human cells, as well as the protection of cells and their components such as membrane lipids and DNA. HELIONORI® patented concentrated active ingredients prepared from *Pyropia umbilicalis* (L.) Kützing contains special marine compounds named mycosporine-like amino acids (MAAs) that act as natural sunscreens in some marine organisms. Helioguard 365 (Mibelle Biochemistry) is a natural UVA-screening compound from sea algae used to protect the skin against photoaging.

However, advances in the understanding of the composition of algae according to their environment, of interactions between the compounds of algae in the metabolism of humans with their microbiome as well as the bio accessibility of algae compounds for human or animal nutrition and health must continue to be explored (Finley, Finley, Ellwood, & Hoadley, 2014; Wells et al., 2017).

3.4 Decent work and economic growth: Promote inclusive and sustainable economic growth, employment and decent work for all (Goal 8), quality education: Ensure inclusive and quality education for all and promote lifelong learning (Goal 4), partnerships for the goals: Revitalize the global partnership for sustainable development (Goal 17)

Sustained and inclusive economic growth can drive progress, create decent jobs for all and improve living standards. This part is highly linked to the first SDG. Seaweed farming is a global business and was carried out in at least 56 countries worldwide in 2018 (12 in Africa, 12 in the Americas, 14 in Asia, 11 in Europe and 7 in Oceania) (FAO, 2020). Farms vary from large industrial enterprises to smaller family-run businesses (Hoegh-Guldberg et al., 2019). More than 99% of the production is found in Asian countries. In 2018, OECD countries accounted for over 60% of the total export value (close to USD 1 billion) of seaweeds traded for direct human consumption or as raw materials to produce other food or non-food products. Europe accounted for nearly half of the world import value (USD 1.3 billion) of seaweed-based thickeners (Giercksky & Doumeizel, 2020; United Nations, 2020a, 2020b). In 2018, global seaweed production was 33 million tons (wet weight), of which 97% was farmed, and 3% came from wild seaweed. Global seaweed production accounted for around 28% of the total aquaculture tonnage. By focusing on marine seaweed resources, developing countries provided an opportunity to access an emerging market, propelled by a diversification of the demand for seaweed products from traditional uses, to bioenergy, cosmetics, and biomedicine applications. Many governments, IGOs, NGOs and private initiatives have initialized ambitious projects to scale up seaweed production outside the major producing areas in Eastern and South-Eastern Asia. The industry doubled in size between 2005 and 2015 (FAO, 2018a, 2018b). In Europe and in Norway several food and food supplement products directly prepared from algae are already certified as organic food for example, and this has given opportunities for producers to access a niche market. The interest in algae creates new markets in different fields and new jobs. In addition to the value chain, sustainable management of coastal resources creates new economic activities based on the exploitation of a raw material, and participates in the local socio-economic development in coastal areas and communities in the World. In Latin America or European coastal communities, fishermen harvesting seaweed from boats and with diving gear complement their income by participating in other fishing such as abalone, sea urchin or fish. Although the seaweed fishery is economically and environmentally sustainable, this livelihood for the fishermen is not always attractive. As explained in Section 3.1., it is therefore important to look at the fishery in a larger context, and the cultivation of seaweeds (as opposed to their harvesting) may actually offer a better alternative to coastal communities, as it can give them the opportunity to increase production and improve productivity and quality. Local farmers sell the seaweeds directly to the processing companies or companies with concessions which directly employ their own workers for harvesting during the year and contracted divers in the summer.

In Norway, the first European producer of the raw materials harvested annually using paddlewheel cutters and seaweed trawlers, corresponds to nearly 200,000 tons of *Laminaria hyperborea* and *Ascophyllum nodosum*. This activity employs 250 people during harvesting and processing for diversified markets (alginate industry), health (additives), agricultural supplies (biostimulants, fertilizers, feed), cosmetics, health and well-being.

In Brittany (France), almost 70.000 tons of fresh seaweed are produced annually (except *Gelidium* which is gathered in the Basque country). In Brittany there is a traditional shoreline seaweed harvest. In 2014, it represented about 6.000 tons. In 2017, it amounted to around 7.700 tons. Nearly 600 tons of macroalgae were used for the decoration of fish stands. Half of the 7.700 tons was mainly *Ascophyllum nodosum*, which is still the most demanded alga. It is used in fertilizers, animal meal and the alginate industry. Only 50–350 tons came from aquaculture. Today, with a growing demand for raw materials and increased pressure on the foreshore due to the coveted coastal areas for marine energy production, port activities, industries and aquaculture, the sector is becoming more structured and is gradually acquiring more efficient resource management tools. Shoreline seaweed harvesting is supervised by the Regional Committee for Sea Fisheries and Marine Farming in Brittany (CRPMEM), a commission made up of fishermen, seaweed harvesters, processing companies and scientists. The Chambre syndicale des algues et des végétaux marins and the syndicat des récoltants d'algues de rives professionnels (The Syndicate of Seaweed and Marine Plants) and the Syndicate of Professional Shoreline Seaweed Harvesters (SRPAR) is strongly involved in the organization of the harvest, the recognition of jobs and the sustainable exploitation of local resources (NETALGAE, 2012). In 2017, more than 60 structures have been identified. Within these structures, 180 people have been identified as working all or part of their time on the seasonal collection of algae (Figs. 7 and 8).

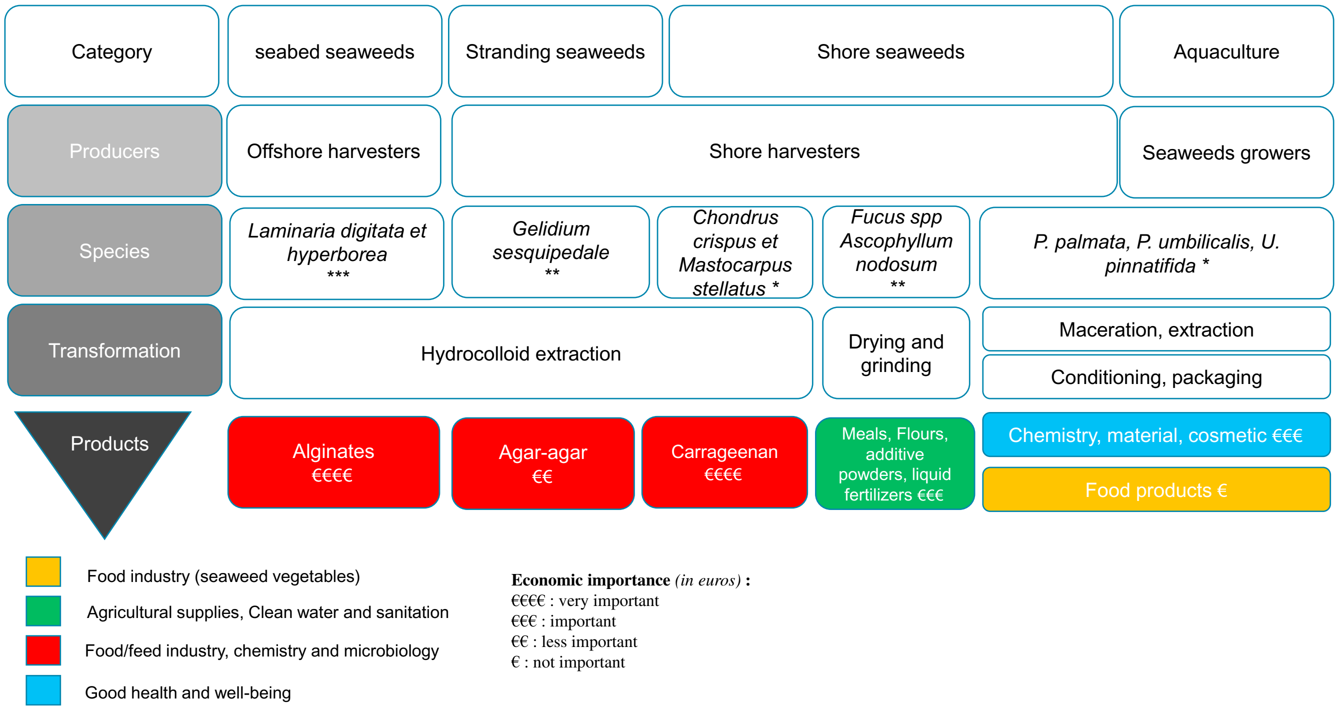

Fig. 7 Organization of macroalgae industry, from seaweeds to uses. Degree of importance in harvested tonnage *(wet tons)* : **** : ≤ 100,000; *** : 50,000; ** : 5000; * : ≤ 1000 (NETALGAE, 2012).

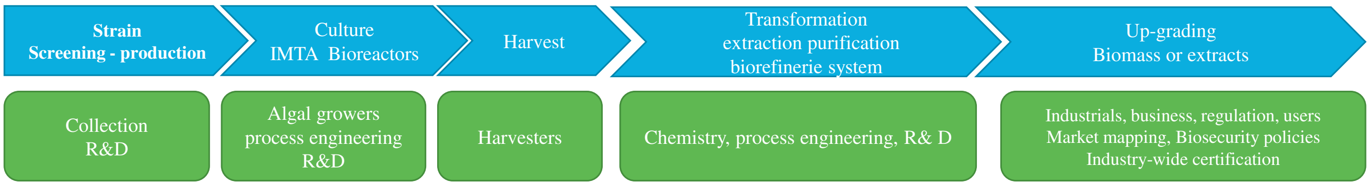

Fig. 8 Blue value chain.

To conclude, seaweed farming could create jobs and improve livelihoods in coastal communities. In low- and middle-income countries, there is a need for increased research on local seaweed communities, the strengthening of value chains and improved resilience in these areas, as well as local capacity building for safe and sustainable production and effective marketing. Development of the industry could be a new source of revenue, especially for emerging economies and vulnerable people. A blue-growth farming coalition platform might also become an anchor for "market mapping initiatives," which are necessary tools when providing directions for sustainable private/public investments (Giercksky & Doumeizel, 2020).

Only a deep understanding and education of the complexity of the marine ecosystem will enable human beings to protect the oceans and organisms populating them, and pave the way for sustainable exploitation of marine resources with decent jobs. The training of young adults in environmental, technological, societal and economic issues is the key to building another form of development of a solidary and united society, to learn to live with dignity, to reduce inequalities, to reduce vulnerabilities. Trained human resources are required in order to provide education to coastal communities, based on best practices for harvesting and cultivation, in order to establish profitable businesses which could provide socio-economic development leading to better living conditions for the rural coastal communities. Several actions are already being carried out around the world in engineering schools, universities and high schools. A first action of knowledge transfer, research and technology development (RTD) by small and medium enterprises (SMEs) is required. Representatives from Norway, Argentina, Brazil, Canada, Chile, Mexico, Peru, and Portugal have established a common working framework in order to support the development of the Latin American seaweed sector. These industry/academia networks encourage cooperation among the seaweed stakeholders; across the project areas; in all aspects related to seaweed production, research, ecosystem services, and management of artisanal and small-scale aquaculture; and traditional and alternative markets and economics (Cottier-Cook et al., 2016; Rebours et al., 2014). The concept of Planetary Health, recently formalized by the launch of a new scientific journal The Lancet Planetary Health, offers a powerful bridge between very different disciplines: it considers that the health of human populations is connected to the health of the environment and that the health of one cannot be examined without examining the other. Planetary Health is defined as the achievement of the highest standard of health, well-being and equity around the world

(Whitmee, Haines, & Beyrer, 2015). The encompassed broad spectrum of disciplines enables the investigation, not only of the effects of environmental changes on human health, but also of human systems (political, economic, social) that govern these effects. The emphasis on the human health consequences of the degradation of natural systems throws into sharp relief the urgency and fragility of the current situation. The Planetary Health Alliance aims to bring together a diverse group of researchers, instructors, policy makers, students and interested individuals in order to understand and communicate the human health impact of global environmental change. MareNet, the worldwide Network of Marine Research Institutions and Documents, provides a set of information services for marine scientists. The website (http://www.marenet.de) gives a detailed description of MareNet and its different services as Marine Research Institutions worldwide or Marine Science Societies and Organizations. In Europe, the European Algae Biomass Association (EABA) promotes mutual interchange and cooperation in the field of biomass production and its use, including biofuels uses and all other utilizations (https://www.eaba-association.org/en). It aims at creating, developing and maintaining solidarity with links between its Members and defending their interests at European and international level. Its main target is to act as a catalyst for synergies among scientists, industrialists and decision makers in order to promote the development of research, technology and industrial capacities in the field of Algae. In France, 15 universities have created the network of Marine Universities around 86 Master's degrees (Ocean Physics Oceanography Environment Marine Chemistry Engineering Economics Marine Energy Ecology Marine Biology Geography Climate Maritime Law Earth Sciences History and Archaeology, …) and 27 PhD degrees (see https://www.universites-marines.fr/fr/formations). To address the increasing challenges facing ocean and coastal ecosystems, the "Interdisciplinary graduate School for the blue planet" (ISblue—https://www.isblue.fr/) was created to train the next generation of ocean innovators and science leaders and place them at the forefront of research to answer the needs of the growing blue economy through top level research-based training. ISblue includes 15 research units and teams showing an internationally recognized expertise in many disciplines (e.g. physical and spatial oceanography, geosciences, biogeochemistry, ecology, microbiology, data analytics and also geography, economics, law, and engineering), all dedicated to tackle questions related to the ocean in all its dimensions and interfaces. ISblue will move interdisciplinarity to an unprecedented level to push back the frontiers in marine science and technology and ocean innovation.

The last and 17th goal of the SDGs emphasizes the need for inclusive partnerships between governments, the private sector and civil society in order to achieve a successful sustainable development agenda. It must place people and the planet at the center and be implemented at global, regional, national and local levels. It implies enhancing cooperation and strengthening domestic resources in all sectors, be it finance, technology, capacity building, trade or systemic issues. Concurrently, over the last few years in sustainability science, the need for transdisciplinarity approaches and an integration of knowledge from experience and science has become conspicuous. The separation of natural and social science in academia led to working in "silos," producing an incomplete understanding of the nature-society interactions and of the integrated dynamics of the "Earth system" as a whole. The necessity for cross disciplinary boundaries also gives rise to challenges of collaboration across complex disciplines. Development of regulations and directives enabling the sustainable exploitation of natural resources must therefore be brought to the national and international political agenda in order to ensure environmental, social, and economic values in the coastal areas around the world. Two conditions are necessary to achieve this: political will and the will of the people. The link between these challenges is solidarity. Examples of partnerships were described in Section 3.1 "No poverty." Indeed, the Red Seaweed Promise of the international company Cargill, the Nagoya protocol or the GlobalSeaweed STAR program highlighted a cooperation and a solidarity between key players from the algae industry.

3.5 Gender equality: Achieve gender equality and empower all women and girls (Goal 5), reduce inequalities: Reduce inequality within and among countries (Goal 10) and peace, justice and strong institutions: Promote just, peaceful and inclusive societies (Goal 16)

Over the last decades, the international community has made considerable progress in lifting people out of poverty. In the 25 years from 1990 to 2015, extreme global poverty has decreased rapidly: the share of the world's population living below the extreme poverty line of $1.90 per day has fallen from 35.6% in 1990 to 10.0% in 2015 (World Bank, 2018). The vulnerable, least developed countries and small island developing States continue to score points in poverty reduction. In this context, international development key players, bilateral development agencies and countries themselves, have united around the goal SDG1 of "ending" extreme poverty by

2030. Concurrently, the development policy debate has been increasingly paying attention to the level of inequality in countries around the world. Inequalities can be estimated in numerous ways, ranging from a denial of individual opportunity to a more structural arrangement of inequality of social conditions. They continue to persist and there are still wide disparities, for example in terms of access to health services and education. They threaten long-term social and economic development which in turn can impact global human health, environmental health and global peace. Thus, the Sustainable Development Goals include both a goal to end poverty (SDG1) and a goal to reduce inequality within and among countries (SDG10).

Among these challenges, gender inequality remains a major barrier toward sustainability. Deep-rooted in every society, women suffer from a lack of accessibility to decent work, education, healthcare and are underrepresented among political and economic decision makers. In many situations, they are victims of violence and discrimination. Therefore, the SDG5 focuses on achieving gender equality and empowering all women and girls. According to the Food and Agriculture Organization, of the estimated 180 million people worldwide working in fisheries and aquaculture, nearly half of them are women (FAO). While this ratio tends to be balanced, the situation is far from equal in terms of rights, recognition and economic independence. All around the world, men and women have historically been involved in fisheries in coastal areas. A common pattern is observed: while men work on boats and go to sea, women are in charge of fisheries activities on the shore, in addition to their household tasks (Hussin & Khoso, 2017). These activities are numerous and crucial to the economy: some examples are the maintenance of the fishing tools, market sales or the creation of added-value products. Unfortunately, women's work is less valued and their contribution to the economy is often invisible. This informal economy creates an insecure labor market and puts women at a greater risk to fall into poverty. As the monetary economy remains associated with the men, women remain dependent on them despite their difficult and time-consuming involvement. This lack of recognition occurs at all levels (local, national, international) and must be addressed in order to achieve sustainability and gender equality (Frangoudes et al., 2019).

Neither a reduction in social inequality nor a gender equality can be advanced without peace and respect for the rule of law. The SDG16 aims to promote peaceful societies at national levels, as well as the role of cooperation at the international level. Access to justice for all and the creation of more peaceful and inclusive societies requires effective and responsible transparent institutions and regulations at all levels. Several actions have been initiated in order to manage and structure the "algae blue chain" in many countries. These actions also aim to reduce economic and social inequalities.

Seaweed farming has been introduced and presented as a way to alleviate poverty in many countries. As mentioned in Section 3.1 "No poverty," the development of this new activity has offered opportunities for the empowerment of women. The cultivation process of these species is based on vegetative propagation and is relatively simple in adequate conditions, as their growth rate can reach 3–8% per day from propagules attached on ropes. Depending on the region and the cultivation methods, such as off-bottom cultivation, rafts, or long-lines, the production cycle before harvesting lasts from 30 to 60 days. In most developing countries, the majority of people involved with seaweed farming are women. Meanwhile in Asia, the gender balance is about even among seaweed farmers (Msuya & Hurtado, 2017).

Seaweed cultivation has become a source of income and livelihood for women living in Tamil Nadu's coastal communities in India or along the coastline of Jepara in Indonesia (Fig. 9). After learning modern seaweed farming, local fisherwomen formed Seaweed Squads to harvest the marine commodity. Thanks to their new job, local women have increased their income and bargaining power, and become role models within and outside their fishing communities (World Bank, 2018). In Tanzania, seaweed farming is unique in that over 80% of its farmers are women. Valderrama, Cai, Hishamunda, & Ridler (2013) reported on studies in Indonesia,

Fig. 9 Local women along the coastline of Jepara in Indonesia. *Photo by Ita Widowati, University of Diponegoro.*

Philippines, India, Tanzania, Solomon Islands and Mexico: they highlighted that for in off-bottom cultivation in shallow water, women were more involved as they can tie and harvest the crop by themselves, while in deeper water they tend to have a smaller role as boats are necessary for raft or floating line techniques. In Tanzania, seaweed farming was introduced in 1989 using pegs and ropes. Farmers have been producing the two carrageenophyta (*Kappaphycus alvarezii* and *Euchema denticulatum*) and agarophyta (*Gracilaria* and *Hypnea*) seaweeds and selling them to buyers who then exported them to Denmark, France, the USA, and Spain. As men were often discouraged by the labor-intensiveness and relatively low profitability of seaweed farming, and hence preferred other activities such as fishing, tourism and the shell polishing trade, it became more a female-oriented activity and an important livelihood source for women. Seaweed farming successfully changed the position of women in society.

This traditional off-bottom method is carried out in shallow intertidal areas by the beach, where conditions for growth used to be optimal. Unfortunately, temperature and salinity can vary rapidly in these environmental conditions and lead to "ice-ice" disease outbreaks and infestation by epiphytes, affecting the quality of the seaweeds (Brugère, Aguilar-Manjarrez, Beveridge, & Soto, 2019). This has been occurring increasingly over the last two decades with the rise of water temperature in the Indian Ocean. In addition to the already volatile and competitive global market, women have also been suffering from the economic and sociocultural burdens of climate change. The industry and all that it has brought to rural women is under threat. In addition, Frocklin, de la Torre-Castro, Lindstrom, Jiddawi, and Msuya (2012) highlighted the potential occupational health hazards linked to seaweed farming in Tanzania: seaweed farmers reported more health issues than non-seaweed farmers such as fatigue, musculoskeletal pain, hunger, respiratory problems, allergies, eye related problems and injuries from hazardous animals and sharp shells in the water.

Initiatives and actions have been implemented in order to address these constraints. Piloted by Dr Flower Msuya, these projects on seaweed farming help fight against social, economic and gender inequalities. The SeaPoWer project started in 2016 in Zanzibar has introduced an improved seaweed farming technology through the use of tubular nets. This method has proven to have a greater tolerance to the roughness of the sea, to provide a higher yield than the off-bottom method and to be more environmentally friendly as it could stimulate fisheries productivity and increase fish catches locally. This technology is used in deeper water and therefore requires swimming and boat handling skills. Most women of Zanzibar do not have these skills and the technology needs to be adapted to the special conditions of Zanzibar as local culture and traditions tend to prevent women from performing some tasks. Women seaweed producers' experience with tubular nets has been very positive overall and presents advantages such as increased productivity, improved welfare and work conditions. While women participants are still not fully independent from men in their community, the SeaPoWer project has boosted their confidence and self-esteem though training and collaboration. The SeaPoWer project has become a concept under which seaweed farming innovation and production cannot be separated from women's empowerment (Brugere et al., 2019). In the same dynamics, the Zanzibar Seaweed Cluster Initiative (www.zasci.webs.com) corresponds to Commercial collaboration with coastal communities—primarily women—now producing, processing and selling commercial products into African and European markets.

The Seaweed Cluster Initiative stands out to be the most successful in Tanzania. The group partners include scientists from the Zanzibar Institute of Marine Science and the government through the Commission for Science and Technology (Costech). The aim of the Seaweed Cluster Initiative is to address these problems and tap the scientific information for the benefit of the farmers and the country at large. For example, the basis of the aim of the Cluster is that there is a possibility to increase seaweed production through modifying the farming technique. Thanks to this Cluster, local people produce more seaweed with the production of *Kappaphycus*, also raising the income of the farmers by enabling them to farm the *Kappaphycus* seaweed as it fetches a high price.

In the Philippines, seaweed farming is a major economic endeavor among the households in the key seaweed production areas because of its high profitability potential relative to the farming effort. Hired workers (mostly female) were paid USD 3.00–4.25/day to remove impurities from seaweed (FAO, 2014). The study of Suyo, Masson, Shaxson, and Luhan (2020) used Social Network Analysis to explore the social structure and the nature of support mechanisms in the production segment of the seaweed value chain to understand the differential in the access of women and men to information, resources, and services. The study shows that there is a strong potential for improving the production and market outcomes by addressing the gaps arising from the current social network systems which include promoting equal access to training, technology, and social relations. There is a need to promote increased knowledge of efficient farming techniques and product standards to minimize losses along the value chain. In the Philippines, and also in other countries, the growth of the seaweed industry will be facilitated if the different stakeholders in the industry are empowered and needs and access of women and men are taken into account in the planning of, and in the formulation of programs aimed at enhancing production and market expansion.

In Indonesia, female involvement is greatest in seaweed cultivation and processing. It is just as important as that of men for the improvement of the coastal economy. The processing of raw seaweed material into various types of products, including products for the food industry, can be an alternative livelihood for fishing households and can be fully managed by women (FAO, 2018a). The Indonesian National Medium-Term Development Plan 2015–2019 explicitly stipulated efforts toward equality in its principles. The main areas foreseen were women's access to higher education (notably the knowledge of seaweed processing is transferred through training activities), health care and labor force opportunities, based on gender inequalities highlighted in the Human Development Index and Gender Development Index, such as gender gaps in education levels and health status and a low representation of women in main decision-making institutions.

In response to the problems of high coordination costs among the poor, efforts are underway in many countries to organize the poor through "self-help groups" (SHGs) or cooperatives—membership-based organizations that aim to promote social cohesion through a mixture of education, access to finance, and connections to wider development programs. The seaweed sector in coastal India has all the potential to rise from the low-income conditions normally associated with basic livelihood activities to higher levels of employment-income-consumption relationships. So far, as many as 1200 families are engaged in seaweed farming, of which 60% of the farmers are women. Seaweed farming has had a remarkably positive effect on the socio-economic status of female farmers as it allows them to engage in an income-earning activity. The SHG consists of members linked by a common bond like caste, sub-caste, community, place of origin, activity, etc., in these "natural groups" or "affinity groups." The SHG provides the benefits of economies in certain areas of the production process by undertaking common action programs like a cost effective credit delivery system, generating a forum for collective learning with rural people, promoting a democratic culture, fostering an entrepreneurial culture, providing a firm base for dialog and cooperation in programs with other institutions, possessing the credibility and power to ensure participation and helping to assess the individual member's management capacity (FAO, 2014; Krishnan & Narayanakumar, 2010). The concept of the SHG was founded on the basic premise that women are more responsible and have a better disposition to work toward achieving social and economic independence.

Through their direct and indirect roles, women contribute to livelihoods, communities, and economics at large. Frangoudes, Gerrard, and Kleiber (2019) cite the example of women in seaweed farming households in Japan who create different high-quality products from seaweed, thereby increasing its value. The emphasis of the quality of their products over quantity is also branded and marketed online. This often requires new skills such as using social media to identify and reach a national market to sell their products. By occupying these positions, women contribute to other activities such as strengthening and revitalizing communities, or food security at a larger scale (Frangoudes et al., 2019).

While successful examples of women's empowerment through seaweed farming are numerous around the world, there is still a long way to go, constraints and difficulties to bypass, efforts and progresses to be made in order to achieve sustainability. Many of the women involved in seaweed farming have low-skilled, low-paid jobs, without contracts or health, safety and labor rights. These communities are particularly fragile to the effects and consequences of climate change and environmental degradation. Sometimes they suffer from the cumulative effects of environmental degradation and measures taken for protecting the environment. Frangoudes et al., (2019) reported the example of how the implementation of Marine Protected Areas, such as in the Gulf of Mannar in India, impacted marginal groups, such as women: they lost their license for seaweed harvesting to harvest seaweeds by diving on the natural wild stocks. Consequently, they lost their only source of income. Women resisted the decision by establishing new management measures (reducing the number of harvesting days and not using modern equipment for example). In addition to the implementation of Marine Protected Area, the fisheries department used to allow only male heads of families to get social benefits, thereby keeping women dependent on men. Following training in 2014, women formulated new claims and, after negotiations, the Tamil Nadu state recognized women seaweed harvesters as fishers, providing them with identity cards and protective equipment. The example shows how women resist unfair decisions and how training and support can emancipate women (Frangoudes et al., 2019).

Some other challenges lie in cultural aspects. For example, in Malaysia, in the Suluk community, women are kept away from seaweed cultivation activities because their monthly menstruations are said to have a negative supernatural effect on seaweed production. In some other areas, women face opposition from male relatives to get involved in seaweed cultivation because it causes shame for the men or because they consider that this role will prevent the women from doing household chores (Hussin & Khoso, 2017).

Unfortunately, COVID-19 has deepened existing inequalities, hitting the poorest and most vulnerable communities the hardest. It has put a spotlight on economic inequalities and fragile social safety nets that leave vulnerable communities to bear the brunt of the crisis. At the same time, social, political and economic inequalities have amplified the impacts of the pandemic. Lakner, Gerszon Mahler, Negre, & Prydz (2020) estimate through a machine-learning algorithm that the pandemic may have driven around 60 million people into extreme poverty in 2020 and, that with current growth rates and inequality index, the number of extreme poor could remain above 600 million in 2030. Since seaweed farming has potential for sustainable development of coastal areas, support and changes toward better working conditions should be encouraged. In order to achieve these SDGs by 2030, research must be transdisciplinary, include women's situations and problems and involve more gender focus by male researchers (Frangoudes et al., 2019).

3.6 Affordable and clean energy: Ensure access to affordable, reliable, sustainable and modern energy for all (Goal 7)

Energy is central to nearly every major challenge and opportunity the world faces today. Be it for jobs, security, climate change, food production or increasing incomes, access to energy for all is essential. Fossil fuels are the current major sources of energy, providing up to 80% of the annual demand. The major industrial and threshold nations, such as the USA, Germany, Japan, China and India, rely heavily on carbonaceous combustibles to supply their domestic industries and to provide for their population.

However, dependence on fossil fuels has decreased recently, dropping from 85% in 2005 to 80%–83% in 2011 due to the development of a number of alternative renewable sources of energy, such as geothermal, wave, wind, solar and biomass (Barbot, Al-Ghaili, & Benz, 2016). Due to diminishing petroleum reserves, deleterious environmental consequences of Green House Gas (GHG) emissions from fossil-based fuels, research on renewable and environmentally friendly fuels has received considerable impetus in recent years. Clean and renewable marine biomass is an excellent contributor to the choice of alternative sources of energy. To ensure access to affordable, reliable, sustainable and modern energy, several technologies have emerged: renewable energy with algae and algae biofuel, algae bio refinery, and eco-friendly innovative green-chemistry-based systems for the sustainable extraction of all major value-added components from the selected algal species.

Biodiesel is a potential fuel that has the ability to replace conventional fossil diesel fuel. Algae are a promising alternative source to the conventional feedstocks for the third-generation biofuel production. They have fast growth rates with up to 4–6 harvest cycles per year and unlike first- and second-generation biofuel feedstocks, macroalgae can be grown in the sea thus eliminating issues relating to land use and water for irrigation. They also have other advantages over a terrestrial biomass: higher carbohydrate levels and biomass yields, their widespread availability, the absence of competition with food or agricultural surfaces and the high quality of their by-products. Their use as a means to capture CO_2 and their suitability for being integrated into wastewater treatments to reduce pollution make them one of the most attractive renewable sources for a sustainable energy strategy, such as their growth in saltwater and municipal wastewater and their lack of requirements for arable land and industrial fertilizers. Macroalgae can be used in the production of biomethane generated from thermal or biological gasification. A wide variety of seaweed species can be anaerobically digested to produce energy-rich methane, which allows flexibility for the choice of biomass source. Bucholc et al. (2014) studied the potential of collecting macrophyta accumulating on the beach from the Baltic sea as a resource for biogas production. The authors suggested that collecting macroalgae removes more nitrogen than phosphorus, that would decrease the N/P ratio in the sea, but not deteriorate the environment. Macroalgae biomass contains substantial reserves of renewable energy, which could be exploited with the appropriate technology for biomass collection/preservation and third-generation gaseous biofuel production as an additive to other carbon-rich biomasses.

Stranding macroalgae from beach and marine areas (e.g. *Ulva* in France, in Venice lagoon and China, *Codium* in Florida USA, Golden tide with *Sargassum* in the Caribbean, …), could be used and it supports beach management for local tourism and decreases seawater pollution caused by massive algal growth (Allen, Browne, Hynes, & Murphy, 2013; Barbot et al., 2016; Kraan, 2013). The process of accessing a suitable beached macroalgae feedstock could be facilitated by the use of supporting technologies, such as satellite imagery and climate simulation models, enabling the prediction and localization of the quality and quantity of eutrophic biomass sources.

Furthermore, seaweed industries generate a considerable quantity of marginal biowaste streams, which could present a potential use in biomethanation. Incorporated into the concept of a circular economy, macroalgal wastes from industry or eutrophication could find a niche in serving as substrates for biomethanation.

Different government research institutes around the world have investigated the development of biorefinery technologies for seaweed, with the objective to produce biofuel (Okoli, Adams, Brigljević, & Liu, 2016). Lehahn, Ingle, and Golberg (2016) used a modeling approach to investigate the global potential for macroalgae. They estimate that 98 Gigatons dry weight of macroalgae per year can be grown globally over a surface area of approximately 108 km^2 and conclude that with near-future aquaculture technologies, offshore cultivation of macroalgae has a huge potential to provide fuels and chemicals for humans. Currently, research efforts into biofuels suitable for gasoline replacement have shifted focus to butanol instead of ethanol because of advantages such as lower miscibility with water, Higher Heating Value (HHV), and better compatibility with existing gasoline engines and fuel pipeline infrastructure. Butanol can be produced from macroalgae using a biochemical route via the acetone, butanol and ethanol (ABE) process. Using *Clostridium beijerinckii* as the fermentation organism Van Der Wal et al. (2013) obtained butanol yields of 0.23 g butanol/g sugars from the green seaweed *Ulva lactuca*. Huesemann, Kuo, Urquhart, Gill, and Roesijadi (2012) carried out a study of butanol fermentation from brown algae (*Saccharina*), but obtained very low butanol yields of 0.12 g butanol/g sugars.

There has also been a considerable discussion over the recent years about the potential of microalgae for the production of biofuels (Suganya, Varman, Masjuki, & Renganathan, 2016). Microalgae can produce 19,000–57,000 L oil/acre in 1 year, better than any previous biodiesel source (Demirbas & Demirbas, 2011). It is converted into biodiesel through a standard transesterification process. The remaining biomass also contains valuable components such as residual lipids, proteins, and soluble polysaccharides, which can be used for the production of bio-oil, bioethanol, biohydrogen, and biogas through various thermo-chemical and biochemical processes for the improvement of an overall energy balance (Deshmukh, Kumar, & Bala, 2019). Various innovative extraction methods like microwave, ultrasound, supercritical fluids and ionic liquids for oil extraction and also the direct transesterification have been evaluated. A higher oil yield was obtained in recent extraction techniques compared to that of conventional solvent extraction techniques. However, in spite of new processes, rapid growth and high lipid content, the production of microalgal biodiesel is an energy intensive and costly affair. Developments in harvesting, drying, oil extraction and direct transesterification stages need to be studied in a global refinery concept. Macroalgae seem to be preferable to microalgae for biofuel production because its plant-like characteristics make it easier to harvest, and its high concentration of carbohydrates in comparison to microalgae make it a potentially better biofuel feedstock.

Management of environmental and health issues are key elements for competitiveness and sustainability. The main challenge, which determines the industrial utilization of algae potential, is the development of efficient extraction methods while preserving most of the intrinsic qualities of the raw material and finding a compromise between the cost of producing sufficient quantities and the quality of compounds in the shortest timeframe. Finding the optimum processing conditions and meeting the principles of green chemistry and green technology will be required for this task. Several procedures exist for extracting and separating biologically active compounds from algae biomass. Indeed, for agriculture, animal feed and health, most of them include water extraction under high pressure and/or alkaline extraction while algal fertilizers are usually prepared with a chemical method where potash lyse and high temperatures are applied. However, such conditions are quite severe and cause the decomposition of most of the biologically active compounds.

In this context, most efforts will be put on cell wall structure disruption in order to enhance the liquefaction of the seaweeds, the release of their internal components and their partial conversion. Another challenge, which will determine the industrial use of algae, is the development of eco-friendly extraction methods in order to preserve the intrinsic qualities of the raw material. Currently, Enzyme-Assisted Extraction (EAE), Microwave Assisted Extraction (MAE) and Ultrasound-Assisted Extraction (UAE) are among the five novel techniques most mentioned in the literature for natural biomass processing (Kadam, Tiwari, & O'Donnell, 2013). The processes are described as feasible and efficient alternatives to traditional extraction methods and could be transposed to a larger scale for seaweed processing. To maximize the added value of the biomass by allowing the co-extraction of valuable components, a strategy of biorefinery will be developed at laboratory and industrial levels. The production of chemicals and materials from renewable feedstocks is an important part of a biobased economy and could potentially make algal biomass and processing steps economically feasible and environmentally beneficial. In this respect it is important to introduce the biorefinery concept that integrates biomass conversion processes in value-added chemicals from biomass, analogous to today's petroleum refineries, which produce multiple fuels and products from crude petroleum (Taylor, 2008). Nowadays, the concept of biorefinery involves the development of eco-friendly processes for sequential recovery of molecules, especially bioactive molecules. Furthermore, EAE, UAE, UAEH (combination of enzymes and sonication) and may be MAEH (combining enzyme and microwave) extraction technologies have demonstrated their interest in the extraction of seaweed biomolecules. These novel extraction technologies enable reducing the use of organic solvents and the treatment time. They also help preserve the activity of target compounds leading to higher extraction yields with a lower cost in comparison to traditional extraction methods. Nevertheless, the main challenge will be transferring them to the industrial scale.

In conclusion, an important point noted by some of these review studies was that despite the potential for macroalgae-based biorefineries, technological improvements in the whole supply chain of macroalgae-based biorefineries (such as seaweed cultivation, harvesting and transporting, pre-treatment, co-digestion, eco-friendly extraction processes and fuel conversion technologies) are needed for economically feasible macroalgae fuel and chemical processes.

3.7 Industry, innovation and infrastructure: Build resilient infrastructure, promote sustainable industrialization and foster innovation (Goal 9) and sustainable cities and communities: Make cities inclusive, safe, resilient and sustainable (Goal 11)

The world is becoming increasingly urbanized. Since 2007, more than half the world's population has been living in cities, and that share is projected to rise to 60% by 2030. The world's cities occupy just 3% of the Earth's land, but account for 60–80% of energy consumption and 75% of carbon emissions. Innovation and technological progress are key to finding lasting solutions to both economic and environmental challenges, such as increased resources and energy-efficiency. Globally, investment in Research and Development (R&D) as a proportion of Gross Domestic Product (GDP) increased from 1.5% in 2000 to 1.7% in 2015 and remained almost unchanged in 2017, but was only less than 1% in developing regions. Basic infrastructures like roads, materials, sanitation, electrical power and water remain scarce in many developing countries.

The most traditional uses of seaweed are for domestic purposes such as for building materials. In some regions, where the quantity of building materials is limited (e.g. Danish islands), seaweed was traditionally used in vernacular architecture. Today, when many countries are threatened with deforestation, some companies are looking for materials which offer a cheaper alternative to wood. Widera (2014) presents some examples of creative and contemporary dwellings made of seaweed as well as brand-new construction methods. For example, seaweed pillows were used as cladding for one holiday house on the Danish island of Læsø by architecture studio Vandkunsten and the non-profit making organization Realdania Byg. Seaweed has some great potential as a building material: it offers good insulation (which is typical for mineral materials), it is non-toxic and fireproof, has great acoustics, humidity control, reduction in CO_2 emissions, low-energy and is biodegradable with a life expectancy of more than 150 years. The seaweed is covered with sea salt and is thus naturally protected against bacteria or insects that could destroy the structure. Seaweed can be visually attractive and its usage establishes the balance between traditional and modern architecture. However, it is important to note that seaweed is a good material choice when it is harvested naturally, i.e. collected on the beach, dried on the meadows (not in ovens) and transported to short distances only. Used in that way seaweed can promote the respect for the uniqueness of regional architecture but simultaneously can be easily adapted to the specific local conditions, including different cultural and climatic factors. This is in accordance with the statement of Peter Sørensen and Winnie Friis Møller that "Architecture is a connecting link between place, climate and human life" (Sørensen & Møller, 2008; Widera, 2014). The preservation initiative of Realdania Byg helped involve local communities in the process which increased the awareness both of the natural and cultural heritage of the island. Consequently, that leads to the protection of the architecture of the past and at the same time to the development of sustainable architecture of the future.

In the study of Ramasubramani, Praveen, and Sathyanarayanan (2016), marine brown algae *Ascophyllum nodosum* was used as additive material to concrete. The authors show that an 8% addition of marine algae to concrete showed an increase in strength properties. Susilorinia et al. (2014) presented an innovative green construction material with a natural algal polymer modified mortar. The authors studied the compressive strength of a natural polymer modified mortar with red seaweed gel (*Eucheuma cottonii*) and seaweed powder (*Gracilaria* sp.). They are very effective in gelling and thickening and may increase the bonding mechanism and density. The research has shown that natural polymer modified mortar with *Gracilaria* sp. powder possesses great compressive strength and splitting tensility.

Paper industries are also dependent on wood-based raw materials. However, global warming and restriction on carbon dioxide emissions make wood exploitation more difficult. The sector of paper and cardboards from non-wood plants and agricultural residues has attracted renewed interest. Some industries using wood resources have been looking for alternate innovative sources to wood with better end products and reduced paper manufacturing expenses. The strength of the material (paper, cardboard) depends on the cellulose content of raw materials. *Cladophora* sp. cosmopolitan green alga can be found in huge masses of a variety of marine and fresh waters. This specie is known to contain fibrillary cellulose, the concentration of which is in the same order of magnitude as wood (Baweja, Kumar, Sahoo, & Levine, 2016). Recently, the TMB Marine Box company (Fort de France) deposited a patent on the fabrication of a cardboard coffin for cremation, using the invasive brown seaweed *Sargassum* as raw material for this process.

In association with the challenge of materials usage, there is the question of plastics. Plastics are undeniably part of our daily lives. Their low price/cost and weight are the main attractions behind their universal use. Unfortunately, the oceans and animals in the world suffer from these huge quantities of plastics (Lavers, Dicks, Dicks, & Fin, 2019; Lebreton et al., 2018; Rochman et al., 2015). In this context, biodegradable and/or biobased polymers are the most extensively explored as new packaging materials. Biodegradable materials are made from both natural and fossil resources and are biodegraded by microorganisms in their natural environment. Biodegradable refers to the ability of materials to break down and return to nature within a short time after disposal (Nešic et al., 2019). The use of algal polysaccharide-based materials can present an eco-friendly technological solution, by reducing dependence on fossil resources and reducing a product's carbon footprint, in comparison to conventional plastic packaging materials. Marine polysaccharides are a group of polymeric carbohydrates with inherent characteristics such as biocompatibility, biodegradability and non-toxicity toward living organisms. The most famous macroalgal-derived bioplastic agents are starch and cellulose derivatives, as well as alginate from brown algae. For example, the starch content of the green algae *Ulva ohnoi* varied from 1.59% to 21.44% depending on growth conditions and seasons. In the study by Prabhu et al. (2019), the authors showed that nutrient starvation significantly increased the starch concentration up to 21.4% on a dry weight basis from *Ulva* cultivated in sea water offshore. The extracted fraction contained 75.45% starch, and the starch extraction yield from the *U. ohnoi* biomass was 50.37%. Production of starch and other nutrients (lipids, proteins, salt, Ulvan) from *U. ohnoi* by offshore farming and extraction in biorefineries, shows great promise to provide a novel and efficient way of improving future food security. Furthermore, Algopack, based in Saint Malo (France; http://www.algopack.com), carried out some assays to produce bioplastics. This company proposes a rigid material made from 100% brown algae industrial waste. However, they are darker and slightly more brittle than conventional plastics. Making plastic bags is not really a concern since they are currently produced from corn. In recent decades many applications of seaweed-based polysaccharides in food packaging and coatings were investigated using agar, carrageenan and alginates. Some works revealed that multilayer films based on κ-carrageenan/agar/clay nanocomposite mixed with polylactide bioplastic or cellulose nanocrystal improved barrier, optical, thermal stability and mechanical properties for the food packaging domain. It was also demonstrated that an alginate-calcium coating enabled the reduction of lipid oxidation, increased moisture content and enhanced the flavor, quality and texture of food. These films could be used as edible coatings for numerous foods such as vegetables and fresh fruit to simply extend shelf life. by A number of studies highlighted that the addition of bioactive agents such as antioxidant or antimicrobial (lemongrass or thyme essential oil, phenolic compounds—tocopherols, lycopene, ascorbic acid) to alginate edible films is more beneficial in comparison with the industrial process using the direct application of bioactive agents in food (Nešic et al., 2019).

Art and culture can be excellent tools to raise awareness and promote sustainable development issues and marine biodiversity aimed at adults, children and students. Many artists give prominence to seaweeds (Painters, designers, plasticians, photographers, …). Jasmine Linington (https://www.jasminelinington.com) has been exploring the potential of seaweed within the fashion and textiles industry while studying for a Master of Fine Arts at the Edinburgh College of Art. Given the devastating environmental impacts from the textile and fashion industry, she became motivated to learn more about seaweed's potential as an alternative for fibers and dye. She makes her own textiles using technology and handmade techniques, SeaCell™, produced by smartfiber AG (https://www.smartfiber.de/en/fibers/seacelltm/) which acts as the base fabric. SeaCell is a cellulose fiber and is non-allergenic and very soft. The seaweed for SeaCell is harvested from the sparsely populated fjords of Iceland in locations where there is no waste and no pollution from shipping traffic. She also explores the extraction of pigment from seaweed to make a natural dye. Currently, she has obtained a license for small-scale harvesting through Scottish Natural Heritage and East Lothian Council. She creates supple kelp sequin jewelry which has a sort of leather-like feel to it.

Designers are pushing boundaries in their quest for sustainability with upcycling, recycling, and using unusual natural products. In the textile domain, technologies move fast, forwards into the future, looking for color from the garden and waste and from plant matter, seaweeds and mushrooms. High tech and slow craft merge effortlessly into new hybrids, able to combine additional functions. The impetuous pace of innovation deals with folding, coiling, braiding and knotting; rethinking textiles first invented in the Bronze Age. Archeology and anthropology are major sources of both knowledge and inspiration, as more and more textiles take on cultural and humanitarian endeavors. The eye-opening concept of reconciling to the impermanent rhythm of living beings invites us to draw on new ways of conceiving our relationship to our milieus, and question where and when the action of our hands can be re-aligned to our thoughts (Buet, 2020). Violaine Buet is designer graduate of the school at ENSCI (Paris, France) (https://violainebuet.com/). Combining biology, materials, cosmology and mesology, she studies in an interdisciplinary way the relationship between living organisms and their environment. Violaine Buet has now developed an innovative multidisciplinary expertise to ennoble the algae from its natural state to novel utilizations from the fine and living arts, haute couture, scenography and decoration, to visual merchandising and industry. She has exhibited her artwork in several exhibitions (Cooper Hewitt of New York, 2020; Philadelphia Museum of Art, 2019; Wawes and Milan, 2019) (Fig 10).

3.8 Responsible consumption and production: Ensure sustainable consumption and production patterns (Goal 12)

Goal number 12 of the 2030 Agenda for Sustainable Development aims to ensure sustainable consumption and production patterns. As defined by the Oslo Symposium in 1994, sustainable consumption and production concerns “the use of services and related products, which respond to basic needs and bring a better quality of life while minimizing the use of natural resources and toxic materials as well as the emissions of waste and pollutants

Fig. 10 Handmade artwork from Violaine Buet.

over the life cycle of the service or product so as not to jeopardize the needs of further generations" (United Nations, 2020b). The value chain of algae has to be considered this way, from the supply of biomass, to consumption through bioprocesses for active compounds isolation and eco-responsible applications. Fig. 11 illustrates the responsible value chain from production to the consumption of algae.

The supply of algae can be obtained by harvesting them in their natural environment and/or by algae farming. For both, a sustainable management and a rational use of the resource have to be considered. In order to sell algae directly for food or for other applications, pre-treatment of the resource and bioprocesses are needed to access active compounds, or to facilitate their use due to a standardization and a stabilization of products. The efficiency of algae-based products is complete when users have some knowledge about algae and know how to apply them. This is why collaborations, partnerships and training are essential to produce and consume resources in a responsible manner. Together and through each one of us, we can sustainably consume natural and local resources by avoiding waste and preserving ecosystem services at the same time.

In 2018, world seaweed production totaled 33 million tons of fresh seaweed with the culture and capture sectors. In 10 years, seaweed production has doubled. The global seaweed industry is worth more than USD 6 billion per annum of which some 85% comprise food products for human consumption (FAO, 2018a). In comparison, 70% of all agricultural land are dedicated to livestock production which represents 30% of the land surface of the planet. 33% of arable lands are not used for food but for feed (FAO, 2006). In accordance with sustainable management and a rational use, algae represent a natural resource with a high potential for food, feed and energy production. While representing only a small fraction of total global seaweed production, harvesting and gathering wild seaweeds has had, and continues to have, an active integral role in many coastal societies, often being linked to the cultural identity of those coastal communities. Interest and demand for algae in the world is increasing, therefore pressure on this resource is more considerable. Resource scientists, managers, conservationists, governments, and other stakeholders need to be proactive in the sustainable management of these vulnerable, yet valuable, resources (Kraan, 2020; Mac Monagail, Cornish, Morrison, Araújo, & Critchley, 2017). Three pressures on wild algae have been identified: the ownership of the resource, its over-exploitation and the impact of mechanical harvesting techniques, such as for example, the boats especially equipped with an articulated hydraulic

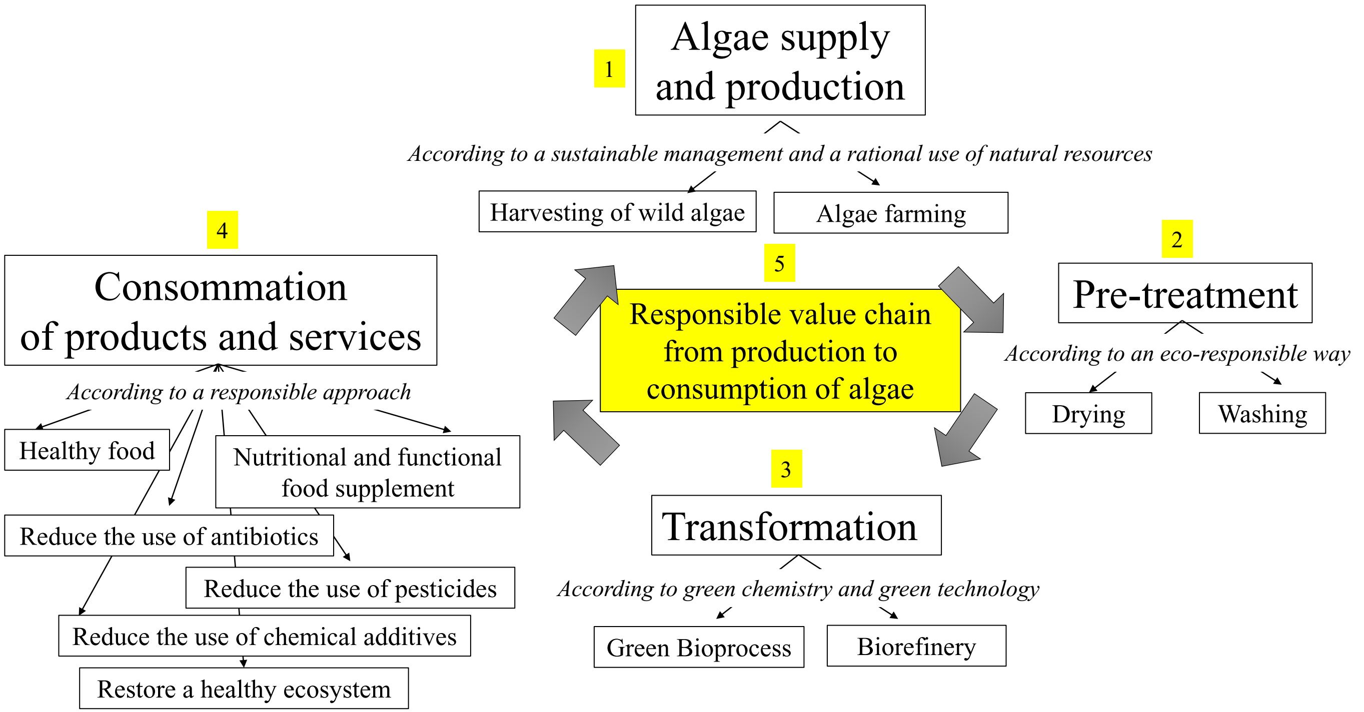

Fig. 11 Responsible value chain from production to consumption of algae. Numbers 1–5 are detailed in Section 3.8. (1) According to a sustainable management and a rational use, algae represent a natural resource with a high potential for its use in food, feed and energy production. (2) According to an eco-responsible way, algae can be prepared for compound extraction and purification. (3) According to green chemistry and green technology, compounds of interest can be isolated. (4) According to a responsible approach, people can consume healthy food, as well as nutritional and functional food supplements for well-being, by indirectly reducing the use of antibiotics in livestock, pesticides in agriculture and chemical additives. Furthermore, some companies can add value to stranded seaweed on beaches which allows the restoration of certain ecosystems. (5) The value chain of algae is responsible if short, local and circular circuits are favored. In addition, all co-products of the bioprocess for algae transformation, from the raw material to the final product, are used and consumed in order to target zero waste.

system called "Scoubidou" that collect brown seaweeds from the genus of *Laminaria* in France. To manage a wild resource, it is important to regulate the quantity and the quality of the resource. Policy regulations and programs have been created by national and international governances and are already in place (See Nagoya protocol and GlobalSeaweed STAR program in Section 3.1 for example). Furthermore, Guiry and Morrison (2013) have shown that the harvested Irish brown seaweed *Ascophyllum* populations, through using simple techniques of 4–5 years of being left fallow, and leaving sufficient material for regeneration, have produced a sustainable yearly harvest of 5.000–28.000 tons wet weight (ww) for the Irish company Arrama, from the late 1940s until the present day (Guiry & Morrison, 2013). Resource monitoring and mapping are important to regulate the growth of seaweeds and their dependent species, to maintain their biological associations which will eventually maintain the equilibrium among various species in the marine ecosystem. Regular monitoring is also important for the seaweed yield estimations and also for observations of harmful algal blooms, these can be useful for fishermen, policy makers, and companies (Beckler et al., 2019; Danish Siddiqui & Abdullah, 2016). The SLAMIR Program aims to measure the impact of the exploitation of brown seaweeds by French companies in order to establish a calendar and regulations for harvesting, in order to preserve the resource (see Section 3.1). According to the development and objectives of the PHYCOMORPH European Guidelines for the Sustainable Aquaculture of Seaweeds (PEGASUS), the development of seaweed aquaculture in Europe faces a number of challenges: the market size, potential environmental impact, preservation of local genetic diversity, regulation of food quality, heavy metals or alien species, cultivation constraints ranging from automation to issues of epiphytism, as well as the need to intensify research—both fundamental and applied. To face these challenges, a United Nations University Policy Brief specifically highlighted recommendations on how to develop this industry sustainably, and identified the key ecological and socio-economic issues preventing the sustainable economic growth of this industry. Recommendations are listed in Table 2. From these, the 4-year multi-national project—GlobalSeaweed STAR—was launched in 2017 (Barbier et al., 2019; Cottier-Cook et al., 2016; see Section 3.1).

In accordance with eco-friendly bioprocesses (Section 3.6), algae can be prepared, and active compounds of interest can be isolated. A pre-treatment of the biomass is required in order to release and dissolve the compounds of potential use. This implies sizing by milling, followed by mechanical,

Table 2 Main recommendations for sustainable aquaculture, UNU policy brief (Barbier et al., 2019; Cottier-Cook et al., 2016).

1	Establish centers of research excellence
2	Establish national seed banks
3	Maintain the genetic diversity in wild stocks
4	Exercise a precautionary approach when introducing new or nonindigenous cultivars to the marine environment
5	Focus on developing and enhancing biosecurity programs
6	Incentivise long-term investment in the industry
7	Incentivise the integration of seaweed and other extractive species with finfish in integrated multitrophic aquaculture (IMTA) systems
8	Develop assessment tools for evaluating spatial planning issues in relation to aquaculture
9	Develop and implement ecosystem-based management models and integrated coastal zone planning
10	Develop regulations and directives that enable a sustainable exploitation of the natural resource
11	Address capacity building and adaptive governance toward seaweed resources
12	Establish management regimes for the sustainable exploitation of the seaweed resources
13	Train human resources to provide education to coastal communities, based on best practices for harvesting and cultivation

chemical or enzymatic methods for the degradation of the cell walls and intercellular matrix. A specific challenge is the high water content of algae (70–90%), which implies that further water addition should be minimized. This pre-treated biomass can be subjected to enzymatic hydrolysis and fermentation for fuels or chemicals, or applied for the isolation of proteins, sulfated polysaccharides and other high-value products (de Carvalho et al., 2020; Skjermo et al., 2014). Continuous, year-round production is required for the economic feasibility of a large-scale production plant. Usually, the biomass will be harvested over a short period, seasonally, when its composition is at its optimum. This implies that the seaweed biomass will need be stored and preserved. In Norway, the brown seaweed *Laminaria hyperborea* harvested for alginate production (approx. 150.000 tons ww annually) is preserved with formaldehyde, which is not a viable option for later biochemical conversion. Other preservation methods applicable for several thousand tons have not yet been defined (Skjermo et al., 2014).

Algae are usually washed with seawater or fresh water to remove undesirable ones, like epiphytes of pieces of plastic, and then either dried or frozen to be sold as such, or prior to extracting the active compounds with higher added value. Fresh, they can also be directly transformed in a short time to keep the intrinsic properties of native compounds from algae.

Drying is a very long-established means of preservation for seaweed. Seaweed lends itself to drying because of its natural salt content. The most common methods utilize natural drying with the heat of sun, dehumidification and air movement. Then different techniques, such as mechanical, by pressing for example, and ultrasonic and microwave treatments, have been used to enhance drying rates (Kadam, Álvarez, Tiwari, & O'Donnell, 2015). Some of them are described in more detail in Section 3.6. Drying could possibly be applied for small biomass volumes intended for high-cost products, but will be too expensive for high-volume/low-cost products. Microalgal biomass pre-treatments for integrated processing into biofuels, food, and feed is an energy-costly step in microalgal biorefineries. Microalgae are sources of nutritional products and biofuels. Their economical processing is challenging, thermolysis being the most cost-efficient processes for further bio-digestion. Using an enzymatic hydrolysis and/or pulsed electric fields and autolysis also are promising steps (de Carvalho et al., 2020).

In accordance with a responsible approach, people can consume healthy food, as well as nutritional and functional food supplements for human well-being by indirectly reducing the use of antibiotics in livestock, pesticides in agriculture and chemical additives. Some companies can add value to stranded seaweed on beaches which allows the restoration of certain ecosystems. This is the case of the French group Olmix for example.

For a responsible food source, by bringing together contributors from the sea to the plate, the "Merci Les Algues, 2020"® association builds sustainable and committed sectors for future generations. The farmers at the heart of the process guarantee the quality of the food that ends up on the consumer's plate. By choosing to reduce the use of antibiotics and pesticides by using natural and local alternatives such as algae, they are committed to responsible nutrition. To encourage them in this direction, they benefit from higher remuneration (www.mercilesalgues.com).

The value chain of algae is viable if short, local and circular circuits are favored. In addition, all co-products of the bioprocess for algae transformation, from the raw material to the final product, are to be used and consumed in order to target zero waste. The biorefinery concept has been identified as the most promising way to create a biomass-based industry (Trivedi, Aila, Bangwal, Kaul, & Garg, 2015 and see Section 3.6).

The study by Peñuela et al. (2018) is a concrete example of this concept at the laboratory scale. The biomass of the carragenophyte *Solieria filiformis* cultured in IMTA system was used to obtain valuable products using a biorefinery approach. Enzymatic-assisted extraction and microwave-assisted extraction were the eco-friendly technologies used to ensure an environmentally friendly valorization of the biomass. Three valuable products were successfully recovered: some water-soluble extract rich in proteins and sulfated polysaccharides suitable as a food supplement; some lipid fraction rich in polyunsaturated fatty acids (PUFAs) with potential to be used in the nutraceutical industry; and a pure iota-carrageenan with a powerful antiviral activity against *Herpes simplex*. To make sense of the algal biorefinery concept, there is a need to establish a proper connection between the various input and output streams of the products.

3.9 Environment: Preservation of the flora, fauna and water and resilience to the climate change thanks to algae (Goals 6, 13, 14, 15)

Considering that our blue planet is composed of a determined space, the role of humanity is to understand it in order to protect and to conserve its ecosystem. Understanding enables the anticipation of the impact that the increase in human population bears on the life below water (SDG 14), on the life on land (SDG 15) and on the quality of water (SDG 6). The preservation of biodiversity and of the environment limits the imbalance of ecosystems risking species extinction and biodiversity loss. Nearly 3 decades ago, a community of eminent scientists warned that humans were on a collision course with the natural world. Twenty-five years later, Ripple et al. (2017) evaluated the human response based on their analysis of time-series data. They concluded that humanity had failed to make sufficient progress over that period in dealing with the environmental challenges. In fact, they concluded that most of these problems had worsened. The original 1992 call was supported by more than 1.700 scientists, while 25 years later over 15.000 scientists added their signatures to the recent declaration (Pyšek et al., 2020; Ripple et al., 2017). Today, it is even more essential to act and to combat climate change and its impacts for the future generations (SDG 13). Fig. 12 summarizes the causes and the consequences of anthropogenic activities on the climate of the Earth. Algae-based

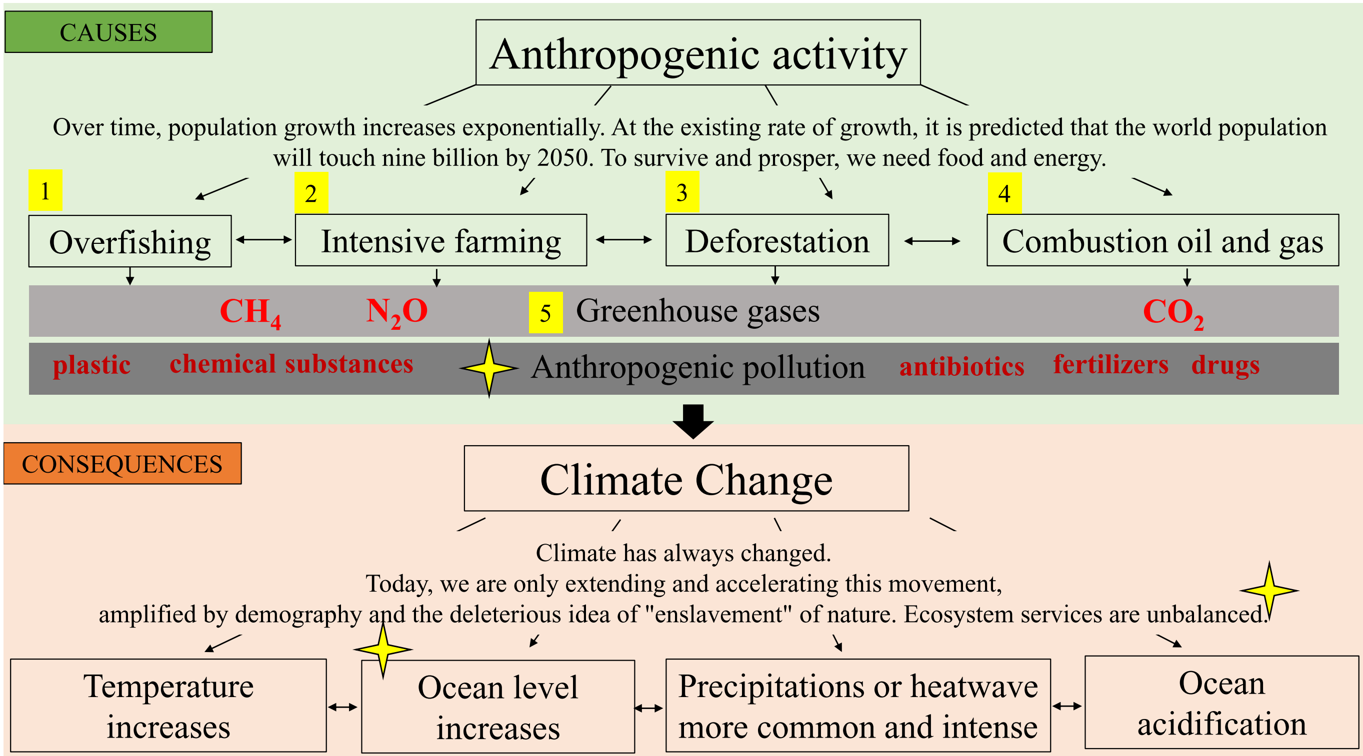

Fig. 12 See figure legend on next page.

solutions are proposed for their numerous attributes toward climate change. They are detailed in this part of the chapter.

The more humans on Earth, the greater the demand for space, food and energy. Under a globalization system, all countries depend on international markets and on a global economy, although inequalities exist and persist (see Section 3.5). Every day, to satisfy basic needs, people around the world consume products from overfishing, intensive farming using high quantities of fertilizers, pesticides, antibiotics and chemicals, deforestation and burning of fossil reserves like oil and gas. All these anthropogenic activities generate greenhouse gases, including essentially carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), and pollution on land and in water (Fig. 13).

Fig. 12 Impact of anthropogenic activities on the Climate of the Earth. Numbers 1–8 are detailed in the text of Section 3.9. For each number, algae-based solutions are proposed. (1) Algae have a real ecological role in marine and fresh water ecosystems. They provide feed and food and oxygen for animals. They neutralize carbon dioxide from the atmosphere. They promote life below water (SDG 14). (2) Algae represent a source of feed and food. To produce them, fertilizers, pesticides, antibiotics, chemicals are not needed. Also, red seaweed can be used to reduce methane emissions from intensive livestock. (3 and 4) Deforestation is caused by the need for arable fields and energy production. To produce algae for feed, food or energy, no arable land is required and life on the land is also protected and conserved (SDG 15). Seaweed farming can take place directly in the sea and Ocean. Furthermore, energy can be produced with algae as mentioned previously in Section 3.6 "Energy clean—Affordable and clean energy—Ensure access to affordable, reliable, sustainable and modern energy for all (SDG 7)." (5) Due to photosynthesis, algae, essentially under the form of phytoplankton, represent the second lung of the Earth. They produce 50% of O_2 and capture CO_2 from the atmosphere that is sequestered in the Ocean. (6) The intensive use of plastics and chemicals contaminate water sources on the Earth. Algae can be produced to filter water. They are renewable agents for bioremediation and enable access to clean water and sanitation (SDG 6). Furthermore, plastic can be made with some seaweeds which avoids polluting the ocean as mentioned in Section 3.7 "Industry, innovation and infrastructure: Build resilient infrastructure, promote sustainable industrialization and foster innovation (SDG 9) and Sustainable cities and communities—Make cities inclusive, safe, resilient and sustainable (SDG 11)." (7) Ecosystem services are unbalanced and consequently the climate changes faster. Today climate actions are essential. Citizens, researchers, politicians and businessmen must act for a responsible and sustainable production and consumption and follow a local, circular, green economy (the doughnut model), (SDG 12 and SDG 13). (8) Ocean levels are increasing which generates an erosion of the coastline, causing houses and buildings to collapse into the sea. A sustainable alternative for coastal dune restoration by sand-trapping fences was developed with algae wrack: AlgoBox®. See Section 3.1 "No poverty: End poverty in all its forms everywhere" (SDG 1).

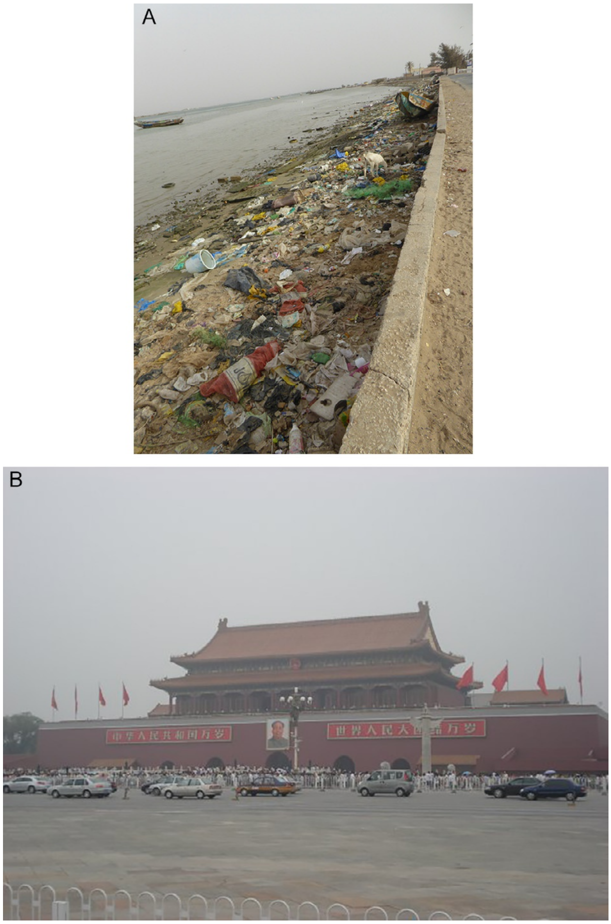

Fig. 13 Anthropogenic pollutions. (A) Plastic residues in Saint Louis, in Senegal (April 2017) and (B) Atmosphere charged with greenhouse gas in Beijing in China (August 2009). *Photos by Burlot AS.*

In his inaugural lesson entitled "Biodiversity: from the ocean to the city" at the Collège de France in 2013, biologist Professor Gilles Boeuf explained that the climate has always changed, but the problem is that today we are extending and accelerating this movement, amplified by demography and the deleterious idea of "enslavement" of nature. According to him, the biodiversity is threatened by four major phenomena: the destruction and contamination of the environment; the predation and over-exploitation of natural resources; the anarchic introduction of species from one environment to another and, finally, global warming (Bœuf, 2014). With time, the greenhouse effect becomes more significant and the global temperature increases while the level of the oceans rises. Precipitation and heatwaves are more intense and more common and the oceans are becoming more acidic (GIEC, 2014). Ecosystems are unbalanced and some species die while others proliferate. Urban looked at over 130 studies to identify the level of risk that climate change poses to species and the specific traits and characteristics that contribute to risk. Results suggest that extinction risks will accelerate with future global temperatures, threatening up to one in six species under current policies. Extinction risks were highest in South America, Australia, and New Zealand, and risks did not vary by taxonomic group (Urban, 2015). Another known and negative impact linked with the climate change is coral bleaching. Coral reefs are the world's most diverse marine ecosystems. They provide billions of dollars in economic value through coastal protection, food, tourism, and pharmaceuticals from the sea. Rapid increases in sea surface temperatures and ocean acidification are increasing the frequency and intensity of coral bleaching events during which corals lose their endosymbiotic algae: a zooxanthella, which is a primary energy source for most reef coral. Its loss causes coral mortality that threatens coral reefs globally (Brown, 1997; Cousteau & Diolé, 1971; Sully, Burkepile, Donovan, Hodgson, & van Woesik, 2019). Biological invasions are also a global consequence of an increasingly connected world and the rise of the size of the human population. Coastal eutrophication is an increasingly significant problem worldwide, where rising nutrient levels in seawater (mainly nitrogen and phosphorus) threaten natural ecosystems. Eutrophication is often directly linked to human activities, largely as a result of fertilizers, local pollution and slurry leakage into freshwater streams eventually reaching coastal areas. Degraded water quality from increased nutrient pollution promotes the development and persistence of many harmful algal blooms and is one of the reasons for their expansion in many nations (Heisler et al., 2008). Algal blooms and their subsequent collapses lead to the development of hypoxia, causing direct effects on the trophic chain leading to community structure changes, biodiversity and habitat loss and overall impoverished ecosystems. The sea lettuce *Ulva* spp. is one of the macroalgal species most commonly linked to the formation of "green tides," where large swaths of the coastal environment are taken over by rapidly proliferating seaweed biomass. The increased occurrence of green tides since the 1970s could however be due to the amplification of fast-growing strains. Fort, Mannion, Fariñas-Franco, and Sulpice (2020) hypothesize that the selective pressure in green tide areas leads to the amplification of *Ulva* genotypes best adapted for this environment. Such selection of fast-growing strains would indicate that green tides are likely to become more prevalent and of higher magnitude over the coming years (Fort et al., 2020). The number of reports of sudden beaching of huge seaweed masses smothering the coastline has increased worldwide in recent years (Fig. 14). These "seaweed tides" can harm tourism-based economies, smother aquaculture operations or disrupt traditional artisanal fisheries (Smetacek & Zingone, 2013).

Algae can be used for the resilience of humanity and for the preservation of biodiversity. For that to happen, it is important to understand the role of each species in the global ecosystem and to change our behavior and our mentality to protect the biodiversity and the environment. Using the best scientific information available to support decision-making is fundamental to the implementation of national and international policies on the conservation of biodiversity and sustainable use of resources as well as the evaluation of ecosystemic trends in both continental and marine areas (Araújo et al., 2016). In relation to the development of public policies for the observation, the preservation and the recovery of natural

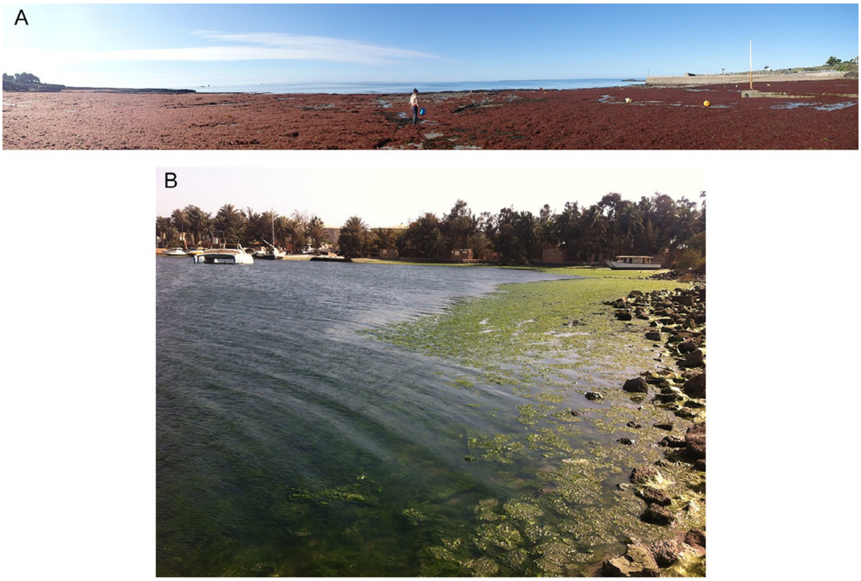

Fig. 14 The number of reports of "seaweed tides" has increased worldwide. (A) Red tide of *Solieria chordalis* in Saint-Gildas-de-Rhuys, France. (B) Green tide of *Ulva* sp. in Dakar, Senegal. *Panel A: Photo taken by Burlot AS in August 2015. Panel B: Photo taken by Burlot AS in August, 2015.*

environments, monitoring networks have been initiated to better understand the putative impact of anthropic pressures on various biotopes. Since 2000, the European Union has included in the Water Framework Directory the investigation of biological communities (phytoplankton, macroalgae, seagrasses, macroinvertebrates and fish) as bio-indicators (biological quality elements or BQEs) to evaluate the ecological status of water bodies (Ar Gall et al., 2016). The project SLAMIR (see Section 3.1) led by a natural park in France gathers data on kelp forests to sustainably manage their exploitation by local companies (Parc Naturel Marin Iroise, 2018).

Algae have a real ecological role in marine and fresh water ecosystems provided that their growth is under control and that they do not proliferate. They procure feed and food and also oxygen for animals. Due to photosynthesis, algae, essentially under the form of phytoplankton, represent the second lung of the Earth. They produce 50% of O_2 and capture CO_2 from the atmosphere that is sequestered by the Ocean.

Sequestering carbon has become part of the portfolio of solutions to mitigate carbon emissions, and thus climate change, through policy and voluntary markets, primarily by land-based reforestation or afforestation and preservation. However, land is limited, creating an interest in a rapidly growing aquatic farming sector of seaweed aquaculture (Froehlich, Afflerbach, Frazier, & Halpern, 2019). Other markets can be expanded to reduce greenhouse gas emissions, such as the use of certain seaweed strains in livestock feed, where its inclusion in cow diets may significantly (by 75%–99%) reduce ruminant methane production (Roque et al., 2019), as well as offshore seaweeds production for biofuel (Fernand et al., 2017 and see Section 3.6). The addition of the red seaweed *Asparagopsis taxiformis* (2% organic matter) or the halogenated methane analog bromoform (5 μM) reduced methane production by over 99% compared to a basal substrate-only control according to the in vitro study of Machado et al. (2018). Fernand et al. (2017) provided a review of algae-based biorefineries with offshore cultivation and consequent biomass conversion into transportation liquid biofuels. In France, by setting a target value of 60% biofuel use with a productivity of 7 g dry weight (DW) of algal biomass per square meter per day and with the possibility to convert 30% of the algal biomass into transportation biofuel, the marine area needed to produce (the 60%) of the total amount of bio-oil consumption for transportation in France is 54,795 km^2. In comparison, the total French marine area's exclusive economic zone with overseas territories included is about 11 million km^2 (Fernand et al., 2017).

Seaweed also procures marine ecosystem support by contributing to increased fish habitats and marine biodiversity, as well as ocean restoration. Seaweeds could potentially serve as the basis of an IMTA (see Section 3.1) with fish and shellfish to increase production while decreasing the environmental impact (Chopin & Robinson, 2004). They promote life under water by providing food (SDG 14). Experiments of Marzinelli, Leong, Campbell, Steinberg, and Vergés (2016) on the dominant habitat-forming macroalga *Phyllospora comosa* (Fucales) that went extinct locally along the metropolitan coastline of Sydney in the 1980s, have indicated that the restoration of key habitat-forming seaweeds not only recovers the algal species but also reduces the risks of losing habitat diversity for epifauna and their consumers. However, restoration of all the original biodiversity associated with specific seaweeds can be a difficult, complex, and long-term process (Marzinelli et al., 2016). By creating coastal habitats, seaweed farming can potentially contribute to some of the ecosystem functions that natural kelp forests and macroalgal beds support. They support high biodiversity, including calcifiers such as lobsters, crabs, mollusks, and crustaceans (Duarte, Wu, Xiao, Bruhn, & Krause-Jensen, 2017).

Furthermore, the intensive use of plastics and chemicals contaminate water sources on the Earth. Algae can also be used as biofilters. They are renewable agents for bioremediation and enable access to clean water and sanitation (SDG 6). Algae can be produced specifically for water filtration. This practice is called phycoremediation, it is the use of algae for the removal, or biotransformation of pollutants and toxic compounds from wastewater and carbon dioxide from effluent air stream. Algae also help remove the elements in water which would have led to the growth of harmful bacteria and consecutive problems. Everywhere in the world, municipal, domestic, agricultural, and industrial sources generate wastewater as an end product. For example, India produces 40 billion liters of wastewater per day (Singh, Tiwari, & Das, 2016). Wastewater is an excellent medium for algal growth, with carbon dioxide addition. Wastewater usage eliminates the need for fresh water and saves nutrient cost since nutrients are in abundance in wastewater. Nutrients such as nitrates and phosphates, help the treatment of the wastewater by assimilating organic and inorganic pollutants into their cells, and eliminate the CO_2 emissions associated with wastewater treatment. Phycoremediation reduces eutrophication. There are also huge amounts of toxic materials like chromium, zinc and lead present in industrial wastewater which are absorbed by algal cells and usually leads to their death (Azarpira, Dhumal, & Pondhe, 2014; Singh et al., 2016). Furthermore, in the context of IMTA systems, several macroalgal species, namely some species from the genus *Gracilaria*, have been shown to be efficient biofilters. Nevertheless, in general, biomass production and nutrient removal were negatively related to the cultivation densities in the system. Seaweed has proved to be an efficient component of land-based IMTA systems, with environmental and potentially economic benefits for the fish farm. Algae can reduce nitrogen and phosphorus as well as heavy metals from water and at the same time value can be added to them as resources for biofuel, active agents and biogas production (Abreu, Pereira, Yarish, Buschmann, & Sousa-Pinto, 2011; Holdt, 2015). Clean water, an efficient and less expansive aquaculture production (fish, mussels) and algal biomasses for biofuel, biogas and the production of active agents are the three major results of the use of algae as biofilters. Furthermore, to avoid plastic pollution in the Oceans; biodegradable plastic can be made with some seaweeds, as mentioned in Section 3.7.

Deforestation is caused by the need for arable fields and energy production. To produce algae for feed, food or energy, no arable land is needed. Therefore, life on land is protected and conserved (SDG 15). Seaweed farming can take place directly in the sea and the Ocean. Furthermore, energy can be produced with algae as mentioned previously in Section 3.6 "Energy clean—(SDG 7)."

In Asia, seaweeds are commonly consumed as "sea vegetables." Most of the *Saccharina japonica*, a brown seaweed, produced in China is used for food. Besides its role as a "health" vegetable, *Saccharina* is also important as raw material for its alginates (texturing and gelling compounds), mannitol and iodine. *Saccharina japonica* is the most important economic seaweed in China. Seaweed farming on artificial floating rafts started in 1952 and production increased steadily until 1980 when the production of 200.000 dry tons (about 1.500.000 wet tons) was achieved. Currently, the yield of *S. japonica* from about 200.000 acres of farms is about 250.000 dry tons from about 2.000.000 wet tons (Guiry, 2020). Some 221 species of seaweed are of commercial value. About 10 species are intensively cultivated, such as brown seaweeds (*Saccharina japonica*, *Undaria pinnatifida* and *Sargassum fusiforme*); red seaweeds (*Porphyra* spp., *Eucheuma* spp., *Kappaphycus alvarezii* and *Gracilaria* spp.); and green seaweeds (*Enteromorpha clathrata*, *Monostroma nitidum* and *Caulerpa* spp.) *S. japonica* and they account for over 33% of the global cultivated seaweed production.

Ecosystem services are unbalanced and the climate is changing faster. Today climate actions are essential. Citizens, researchers, politicians and businessmen act for a responsible and sustainable production and consumption following a local, circular and green economy (the doughnut model) (SDG 12 and SDG 13).

In 2020, a seaweed manifesto was published in open access. It has been initiated by Lloyd's Register Foundation, an independent global charity that supports research, innovation and education with a mission to make the world a safer place. The work has been actively supported by the Sustainable Ocean Business Action Platform of the United Nations Global Compact. The Action Platform is taking a comprehensive view on the role of the ocean in achieving the 17 Sustainable Development Goals. The seaweed manifesto is a visionary document for the industry exploring the opportunities and benefits, as well as outlining the challenges and barriers for the responsible development of the industry. It shows the importance of the algae sector, considered by the United Nations, playing a significant role in achieving the Global Goals by contributing to food safety and security, climate change mitigation, poverty alleviation and support to marine ecosystems. The seaweed manifesto was also elaborated to create increased interest and active contributions to the responsible development of the industry from international donors, intergovernmental organizations, nongovernmental organizations, research centers and international companies (Lloyd's Register Foundation, 2020).

The solutions based on nature are defined by the International Union for Conservation of Nature (IUCN) as actions aiming to protect, manage and restore sustainably natural or modified ecosystems, which respond effectively and adaptively to societal challenges by supplying the benefits in terms of human well-being and biodiversity (Lehmann, 2020). Until today, ecosystem services have been largely exploited by humans and some of them tend to run out. It is the case for fossil reserves for example. Ecosystem services are the benefits people obtain from ecosystems. These include provisioning services such as food, water, timber, and fiber; regulating services that affect climate, floods, disease, waste, and water quality; cultural services that provide recreational, esthetic, and spiritual benefits; and supporting services such as soil formation, photosynthesis, and nutrient cycling. The human species, while buffered against environmental changes by culture and technology, is fundamentally dependent on the flow of ecosystem services. This concept was spread by the Millennium Ecosystem Assessment (MA) that was carried out between 2001 and 2005 to assess the consequences of ecosystem change for human well-being. It also established the scientific basis for actions needed to enhance the conservation and sustainable use of ecosystems and their contributions to human well-being. The MA responds to government requests for information received through four international conventions—the Convention on Biological Diversity, the United Nations Convention to Combat Desertification, the Ramsar Convention on Wetlands, and the Convention on Migratory Species—and is also designed to meet the needs of other stakeholders, including the business community, the health sector, nongovernmental organizations, and indigenous peoples. The sub-global assessments also aimed to meet the needs of users in the regions where they were undertaken (Millennium Ecosystem Assessment, 2005). Nevertheless, the Earth is limited and these ecosystems services become unbalanced if nothing changes. Nine planetary boundaries were defined: freshwater use, biochemical flows, ocean acidification, atmospheric aerosol loading, stratospheric ozone depletion, novel entities, climate change, biosphere integrity and land-system change. If humanity does not exceed these boundaries, it will be possible to continue to develop and to prosper for the future generations. To ensure a safe and equitable space, the global economy needs to change. The British economist Kate Raworth supports the idea that we must write a novel economy manual by starting from the planetary boundaries and Human Rights. She is the author of the book titled "Doughnut Economics" (Lehmann, 2020). Today, politicians and businessmen consider this doughnut theory as explained in Section 3.8 on Responsible Production and Consumption and in Section 3.1 with the examples of the Nagoya protocol and the GlobalSeaweedSTAR program.

Other actions have taken place for the conservation, restoration of biodiversity and ecosystem services in disturbed environments. Innovated applications have been initiated by citizens around the world. In 2010, after a few years spent researching algae, the marine biologist Anne-Gaëlle Jacquin started a journey around the world, called the "Route des Algonautes" to talk to people working with algae. She interviewed more than 150 people. One of the objectives is to share with everyone, including children at school, the many virtues of algae and make them known and available. In 2016, she created the website www.algonauts.org to share this knowledge over the web. It's a place where she explores the latest developments in sustainability and algae in her on-going method (Jacquin, 2020). Another concrete action is the one of native divers in Japan for the removal of the sea urchins, the causative grazer of kelp beds. With less sea urchins, the kelp beds were restored and the fish returned. The aged and depopulated fishermen on the coast had food again thanks to these volunteer divers (Watanuki et al., 2010).

A sustainable alternative for coastal dune restoration by sand-trapping fences was developed with algae wrack: AlgoBox® (Fig. 15). Throughout

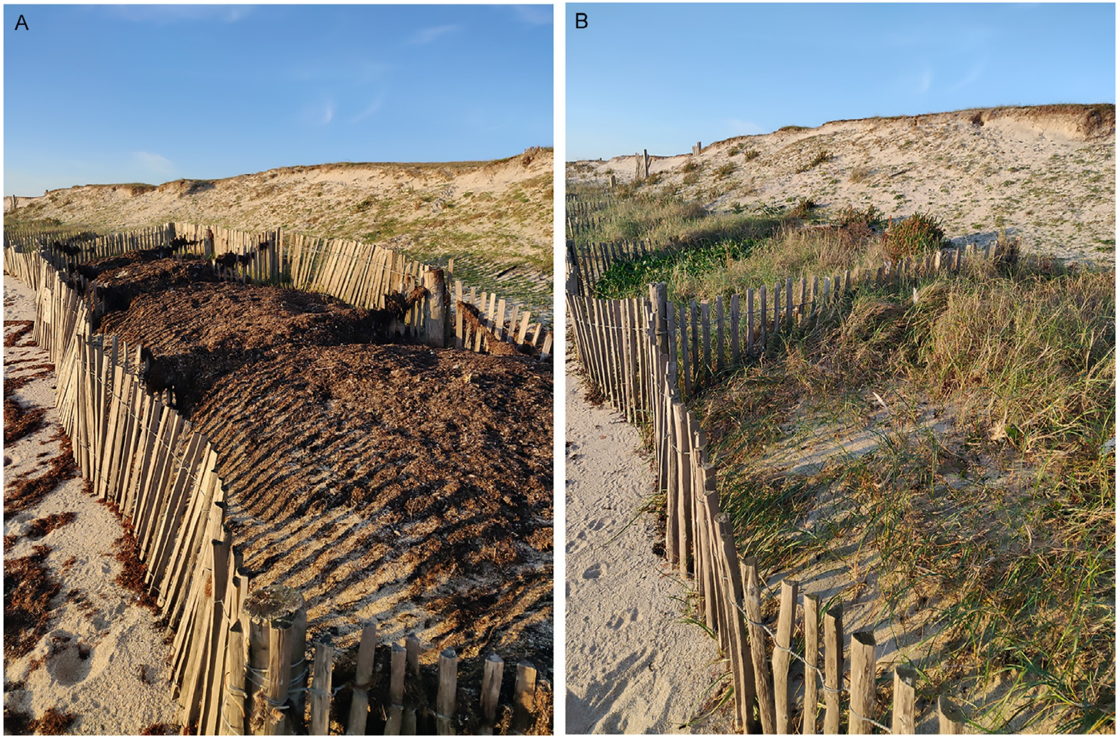

Fig. 15 The presence of (A) sustainable alternative for coastal dune restoration by sand-trapping fences (B) organic matter released thanks to Rhodophyta Solieria chordalis biomass decomposition in South Brittany (France). *"Photo by N. Bourgougnon."*

the world, numerous coastlines are subjected to severe erosion. The topography of these coasts is characterized mainly by cliffs and headlands, embayed beaches and "low-tide-terrace" pocket beaches. Wrack deposits can form significant seasonal accumulations on the beaches, thus impacting their morphology and ecosystem (Sedrati, 2018; Sedrati & Cochet, 2015).

Finally, as synthetized in Fig. 13, ocean levels are increasing, causing erosion of the coastline and resulting potentially in houses collapsing and falling into the sea. Development of seaweed farming can bring solutions to this issue. The canopies of farmed seaweeds, like those of wild seaweeds, dampen wave energy and hence, serve as live coastal protection structures buffering against coastal erosion. For example, Norwegian kelp forests dominated by the brown seaweed *Laminaria hyperborea* have been reported to reduce wave heights by up to 60%. A key difference, in terms of the capacity of farmed seaweed to reduce wave energy is that their canopies are suspended from the surface rather than being benthic. The wave-attenuating effect depends on the extent and structure of the seaweed habitat as well as the energy involved, as seaweed farms will be damaged during high-energy storms (Duarte et al., 2017).

Furthermore, algae aquaculture can be a tool for carbon fixation, reducing nutrient loads in coastal waters, and also for the conservation of ecosystem services. In 2019, the European Marine Research Network EUROMARINE supported a workshop called "RECOVER: Seaweed aquaculture: A promising tool for the restoration and sustainable development of coastal environments or an expensive end-of-pipe technology?" Twenty experts from eight EU countries, Israel and Senegal participated. The interactions of algae monocultures with their environment and their use in integrated marine aquaculture are increasingly attracting scientific interest because of their key roles in marine biodiversity, ecological processes and biogeochemical cycles. Demonstration regions included the Bay of Dakar (a heavily polluted environment with direct sewage disposal), Madeira (coastal waters described as a disturbed environment in nutrient-poor water), and the southern Baltic Sea (habitat over-fertilized by nutrient-rich surface runoff).

4. Conclusion

A holistic approach is needed for addressing complex global problems and must involve all stakeholders, researchers, policy makers, civil society, scientific and non-scientific communities. That requires efforts for finding methods and languages across and beyond each individual discipline, and covering a wide spectrum of disciplines for which education and progress must be nurtured. As described in the previous goals in this article, seaweeds withhold a tremendous potential for facing sustainability challenges. Seaweeds propose environmental benefits: renewable biomass and fast growth, CO_2 uptake and storage, increased biodiversity and dissolved oxygen in the sea, increased fish stocks in the vicinity of farms, biofilter ability (bioremediation), assistance in reducing coastal eutrophication and improve water quality. IMTA—Integrated aquaculture for cleaner waters and improved resource utilization, Seaforestation—planting artificial seaweed forests for the benefit of the environment, help mitigate climate change and ocean acidification (through large-scale cultivation). The numerous applications could also provide environmental services and an important source of livelihood in coastal regions. This potential is still underexploited. Seaweed science and industry can contribute deeply in the Planetary Health discussions.

References

Abreu, M. H., Pereira, R., Yarish, C., Buschmann, A. H., & Sousa-Pinto, I. (2011). IMTA with Gracilaria vermiculophylla: Productivity and nutrient removal performance of the seaweed in a land-based pilot scale system. *Aquaculture*, *312*, 77–87.

Adl, S. M., Simpson, A. G., Lane, C. E., Lukeš, J., Bass, D., Bowser, S. S., et al. (2012). The revised classification of eukaryotes. *The Journal of Eukaryotic Microbiology*, *59*, 429–493.

Allen, E., Browne, J., Hynes, S., & Murphy, J. D. (2013). The potential of algae blooms to produce renewable gaseous fuel. *Waste Management*, *33*, 2425–2433.

Ar Gall, E., Le Duff, M., Sauriau, P. G., De Casamajor, M. N., Gevaert, F., Poisson, E., et al. (2016). Implementation of a new index to assess intertidal seaweed communities as bioindicators for the European Water Framework Directory. *Ecological Indicators*, *60*, 162–173.

Araújo, R. M., Assis, J., Aguillar, R., Airoldi, L., Bárbara, I., Bartsch, I., et al. (2016). Status, trends and drivers of kelp forests in Europe: An expert assessment. *Biodiversity and Conservation*, *25*, 1319–1348.

Azarpira, H., Dhumal, K., & Pondhe, G. (2014). Application of phycoremediation technology in the treatment of sewage water to reduce pollution load. *Advances in Environmental Biology*, 2419–2424.

Beckler, J. S., Arutunian, E., Moore, T., Currier, B., Milbrandt, E., & Duncan, S. (2019). Coastal harmful algae bloom monitoring via a sustainable, sail-powered mobile platform. *Frontiers in Marine Science*, *6*, 587. https://doi.org/10.3389/fmars.2019.00587.

Barbier, M., Charrier, B., Araujo, R., Holdt, S. L., Jacquemin, B., & Rebours, C. (2019). In M. Barbier, & B. Charrier (Eds.), *PEGASUS—PHYCOMORPH European guidelines for a sustainable aquaculture of seaweeds, COST action FA1406*. France: Roscoff.

Barbot, Y. N., Al-Ghaili, H., & Benz, R. (2016). A review on the valorization of macroalgal wastes for biomethane production. *Marine Drugs*, *14*, 120–129.

Baweja, P., Kumar, S., Sahoo, D., & Levine, I. (2016). Macroalgae systematics. In J. Fleurence & I. Levine (Eds.), *Seaweed in health and disease prevention*. Elsevier. ISBN: 9780128027936 (Chapter 3).

Bedoux, G., Hardouin, K., Burlot, A. S., & Bourgougnon, N. (2014). Bioactive components from seaweeds: Cosmetic applications and future development. In N. Bourgougnon, & J. P. Jacquot (Eds.), *71. Advance botanical research* (pp. 345–378). London, Cambridge, Oxford: Elsevier.
Bœuf, G. (2014). *La biodiversité, de l'océan à la cité. Collège de France/Fayard Collection « Leçons inaugurales du Collège de France ». Vol. 241* (p. 85). ISBN : 978-2-213-68148-1.
Boudouresque, C. F. (2015). Taxonomy and phylogeny of unicellular eukaryotes. In J. C. Bertrand, P. Caumette, P. Lebaron, R. Matheron, P. Normand, & T. Sime-Ngando (Eds.), *Environmental microbiology: fundamentals and applications. Microbial ecology* (pp. 191–257). Springer publication.
Brown, B. E. (1997). Coral bleaching: Causes and consequences. *Coral Reefs*, *16*, 129–S138.
Brown, M. W., Sharpe, S. C., Silberman, J. D., Heiss, A. A., Lang, B. F., Simpson, A. G. B., et al. (2013). Phylogenomics demonstrates that breviate flagellates are related to opisthokonts and apusomonads. *Proceedings of the Royal Society B*, *280*, 1755–1761.
Brugère, C., Aguilar-Manjarrez, J., Beveridge, M. C. M., & Soto, D. (2019). The ecosystem approach to aquaculture 10 years on – a critical review and consideration of its future role in blue growth. *Reviews in Aquaculture*, *11*(3), 493–514. https://doi.org/10.1111/raq.12242.
Bucholc, K., Szymczak-Żyła, L., Lubecki, L., Zamojska, A., Hapter, P., Tjernström, E., et al. (2014). Nutrient content in macrophyta collected from southern Baltic Sea beaches in relation to eutrophication and biogas production. *Science of the Total Environment*, *473–474*, 298–307.
Buet, V. (2020). From seaweed to seaweeders. In *Advances botanical research: Vol. 95. Seaweeds around the world: State of art and perspectives*. ISBN: 978-0-08-102710-3 (Chapter 12).
Burki, F., Kaplan, M., Tikhonenkov, D. V., Zlatogursky, V., Minh, B. Q., Radaykina, L. V., et al. (2016). Untangling the early diversification of eukaryotes: A phylogenomic study of the evolutionary origins of Centrohelida, Haptophyta and Cryptista. *Proceedings. Biological Sciences*, *283*, 2015–2802.
Cardozo, K. H. M., Guaratini, T., Barros, M. P., Falcão, V. R., Tonon, A. P., Lopes, N. P., et al. (2007). Metabolites from algae with economical impact. *Comparative Biochemistry and Physiology Part C: Toxicology & Pharmacology*, *146*, 60–78.
Cherry, P., Yadav, S., Strain, C. R., Allsopp, P. J., McSorley, E. M., Ross, R. P., et al. (2019). Prebiotics from seaweeds: An ocean of opportunity? *Marine Drugs*, *17*, 327.
Chopin, T., & Robinson, S. (2004). Defining the appropriate regulatory and policy framework for the development of integrated multi-trophic aquaculture practices: Introduction to the workshop and positioning of the issues. *Bulletin of the Aquaculture Association of Canada*, *104*, 4–10.
Cian, R. E., Drago, S. R., de Medina, F. S., & Martinez-Augustin, O. (2015). Proteins and carbohydrates from red seaweeds: Evidence for beneficial effects on gut function and microbiota. *Marine Drugs*, *13*, 5358–5383.
Convention on Biological Diversity. (2015). https://www.cbd.int/abs/about/.
Cottier-Cook, E. J., Nagabhatla, N., Badis, Y., Campbell, M., Chopin, T., Dai, W., et al. (2016). *Safeguarding the future of the global seaweed aquaculture industry*. United Nations University (INWEH) and Scottish Association for Marine Science Policy Brief. ISBN 978-92-808-6080-1.
Cousteau, J. Y., & Diolé, P. (1971). *La vie et la mort des coraux*. France: Flammarion.
Couteau, C., & Coiffard, L. (2016). Chapter 14. Seaweed application in cosmetics. In J. Fleurence, & I. Levine (Eds.), *Seaweed in health and disease prevention* Elsevier. eBook.
Danish Siddiqui, M., & Abdullah, M. (2016). Evaluation of World View-2 satellite data for mapping seaweed beds along Karachi Coast. In *41st COSPAR Scientific Assembly, abstracts from the meeting that was to be held 30 July–7 August at the Istanbul Congress Center (ICC), Turkey, but was cancelled*. See http://cospar2016.tubitak.gov.tr/en/.

de Carvalho, J. C., Magalhães, A. I., de Melo Pereira, G. V., Medeiros, A. B. P., Sydney, E. B., Rodrigues, C., et al. (2020). Microalgal biomass pretreatment for integrated processing into biofuels, food, and feed. In *Vol. 300. Bioresource Technology* (pp. 122–719). Elsevier Ltd.

De Jesus Raposo, M. F., de Morais, A. M., & de Morais, R. M. (2016). Emergent sources of prebiotics: Seaweeds and microalgae. *Marine Drugs*, *14*, 27–34.

de Reviers, B. (2003). *Biologie et phylogénie des algues, Tome 1 and 2. France : Belin sup*.

Déléris, P., Nazih, H., & Bard, J. M. (2016). Seaweeds in human health. In J. Fleurence, & I. Levine (Eds.), *Seaweed in health and disease prevention* Elsevier. eBook.

Demirbas, A., & Demirbas, F. M. (2011). Importance of algae oil as a source of biodiesel. *Energy Conversion and Management*, *52*, 163–170.

Deshmukh, S., Kumar, R., & Bala, K. (2019). Microalgae biodiesel: A review on oil extraction, fatty acid composition, properties and effect on engine performance and emissions. *Fuel Processing Technology*, *191*, 232–247.

Duarte, C. M., Wu, J., Xiao, X., Bruhn, A., & Krause-Jensen, D. (2017). Can seaweed farming play a role in climate change mitigation and adaptation?. *Frontiers in Marine Science*, *4*, 100–108.

El Gamal, A. A. (2010). Biological importance of marine algae. *Saudi Pharmaceutical Journal*, *18*, 1–25.

FAO. (2006). *Livestock long shadow*. Rome: Food and Agriculture Organisation of the United Nations.

FAO. (2014). *The state of the world fisheries and aquaculture 2014* (p. 223). Rome: FAO.

FAO. (2015). *FAO global aquaculture production database updated to 2013—Summary information*. Rome: FAO.

FAO. (2016). The state of the world fisheries and aquaculture 2016. *Contribution to food security and nutrition for all*. Rome. 200 pp.

FAO. (2018a). The global status of seaweed production, trade and utilization. In F. Ferdouse, Z. Yang, S. L. Holdt, P. Murúa, R. Smith, & FAO Consultants (Eds.), *Vol. 124. Globefish research programme*.

FAO. (2018b). *The state of world fisheries and aquaculture 2018—Meeting the sustainable development goals*. Rome. Licence: CC BY-NC-SA 3.0 IGO.

FAO. (2020). *La durabilité en action. La situation mondiale des pêches et de l'aquaculture 2020*. Rome: FAO. https://doi.org/10.4060/ca9229fr.

Fernand, F., Israel, A., Skjermo, J., Wichard, T., Timmermans, K. R., & Golberg, A. (2017). Offshore macroalgae biomass for bioenergy production: Environmental aspects, technological achievements and challenges. In *Vol. 75. Renewable and sustainable energy reviews* (pp. 35–45). Elsevier Ltd.

Finley, J. W., Finley, J. W., Ellwood, K., & Hoadley, J. (2014). Launching a new food product or dietary supplement in the United States: Industrial, regulatory, and nutritional considerations. *Annual Review of Nutrition*, *34*, 421–447.

Fleurence, J., & Levine, I. (2016). In J. Fleurence, & I. Levine (Eds.), *Seaweed in health and disease prevention* Elsevier. ebook.

Fort, A., Mannion, C., Fariñas-Franco, J. M., & Sulpice, R. (2020). Green tides select for fast expanding Ulva strains. *Science of the Total Environment*, *698*, 134–337.

Frocklin, S., de la Torre-Castro, M., Lindstrom, L., Jiddawi, N., & Msuya, F. (2012). Seaweed mariculture as a development project in Zanzibar, East Africa: A price too high to pay? *Aquaculture*, *356*, 30–39.

Frangoudes, K., Gerrard, S., & Kleiber, D. (2019). Situated transformations of women and gender relations in small-scale fisheries and communities in a globalized world. *Maritime Studies*, *18*, 241–248.

Froehlich, H. E., Afflerbach, J. C., Frazier, M., & Halpern, B. S. (2019). Blue growth potential to mitigate climate change through seaweed offsetting. *Current Biology*, *29*(8), 3087–3093.

Gattuso, J. P., Gentili, B., Duarte, C. M., Kleypas, J. A., Middelburg, J. J., & Antoine, D. (2006). Light availability in the coastal ocean: Impact on the distribution of benthic photosynthetic organisms and their contribution to primary production. *Biogeosciences*, *3*, 489–513.

GIEC. (2014). *Changement climatique2014*. Rapport de synthèse.

Giercksky, E., & Doumeizel, V. (2020). *Seaweed revolution: A manifesto for a sustainable future* (p. 16). Lloyd's Register Foundation.

Ginigaddara, G. A. S., & Lankapura, A. I. Y. (2018). Farmer's perspective on importance and constraints of seaweed farming in Sri Lanka. *Current Investigations in Agriculture and Current Research*, *3*(1). https://doi.org/10.32474/CIACR.2018.03.000151. CIACR. MS.ID.000151.

Guiry. (2020). *Saccharina cultivation in China. The Seaweed Site: information on marine algae*. Site © M.D. Guiry 2000–2020. Online on July 16th 2020 http://www.seaweed.ie/aquaculture/kelp_china.php.

Guiry, M. D., & Morrison, L. (2013). The sustainable harvesting of Ascophyllum nodosum (Fucaceae, Phaeophyceae) in Ireland, with notes on the collection and use of some other brown algae. *Journal of Applied Phycology*, *25*, 1823–1830.

Hamed, I., Özogul, F., Özogul, Y., & Regenstein, J. M. (2015). Marine bioactive compounds and their health benefits: A review. *Comprehensive Reviews in Food Science and Food Safety*, *14*, 446–465.

Harnedy, P. A, & FitzGerald, R. J. (2011). Bioactive proteins, peptides, and amino acids from macroalgae. *Journal of Phycology*, *47*(2), 218–232.

Heisler, J., Glibert, P. M., Burkholder, J. M., Anderson, D. M., Cochlan, W., Dennison, W. C., et al. (2008). Eutrophication and harmful algal blooms: A scientific consensus. *Harmful Algae*, *8*, 3–13.

Herrero, M., & Thornton, P. K. (2013). Livestock and global change: Emerging issues for sustainable food systems. *Proceedings of the National Academy of Sciences of the United States of America*, *110*, 20878e20881.

Hoegh-Guldberg, O., Caldeira, K., Chopin, T., Gaines, S., Haugan, P., Hemer, M., et al. (2019). *The ocean as a solution for climate change: Five opportunities for action*. Washington, DC: World Resources Institute. Report. https://oceanpanel.org/sites/default/files/2019-10/HLP_Report_Ocean_Solution_Climate_Change_final.pdf.

Holdt, S. L. (2015). *The commercial IMTA and future seaweed biofilter potential in Denmark*. Sound/Visual Production.

Holdt, S., & Kraan, S. (2011). Bioactive compounds in seaweed: Functional food applications and legislation. *Journal of Applied Phycology*, *23*, 543–597.

Huesemann, M. H., Kuo, L.-J., Urquhart, L., Gill, G. A., & Roesijadi, G. (2012). Acetone-butanol fermentation of marine macroalgae. *Bioresource Technology*, *108*, 305–309.

Hussin, H., & Khoso, A. (2017). Seaweed cultivation and coastal communities in Malaysia: An Overview. *Asian Fisheries Science*, *30*, 87–100.

Ioannou, E., & Roussis, V. (2009). Natural products from seaweeds. In *Biomedical and life science* (pp. 51–81). Springer.

Jacquin, A. G. (2020). *The Algonauts project*. Website consulted on July 17th 2020 http://algonauts.org/.

Jakobsdottir, G., Nyman, M., & Fak, F. (2014). Designing future prebiotic fiber to target metabolic syndrome. *Nutrition*, *30*, 497–502.

Jesumani, V., Du, H., Pei, P., Aslam, M., & Huang, N. (2020). Comparative study on skin protection activity of polyphenol-rich extract and polysaccharide-rich extract from *Sargassum vachellianum*. *PLoS One*, *15*, e0227308.

Kadam, S. U., Álvarez, C., Tiwari, B. K., & O'Donnell, C. P. (2015). Processing of seaweeds. In *Seaweed sustainability: food and non-food applications* (pp. 61–78). Elsevier Inc.

Kadam, S. U., Tiwari, B. K., & O'Donnell, C. P. (2013). Application of novel extraction technologies for bioactives from marine algae. *Journal of Agricultural and Food Chemistry*, *61*, 4667–4675.
Kassem, A. A., Farid, R. M., Elsayed Issa, D. A., Khalil, D. S., Abd-El-Razzak, M. Y., Saudi, H. I., et al. (2015). Development of mucoadhesive microbeads using thiolated sodium alginate for intrapocket delivery of resveratrol. *International Journal of Pharmaceutics*, *487*, 305–313.
Keith, S. A., Kerswell, A. P., & Connolly, S. R. (2014). Global diversity of marine macroalgae: Environmental conditions explain less variation in the tropics. *Global Ecology and Biogeography*, *23*, 517–529.
Kinley, R. D., Martinez-Fernandez, G., Matthews, M. K., de Nys, R., Magnusson, M., & Tomkins, N. W. (2020). Mitigating the carbon footprint and improving productivity of ruminant livestock agriculture using a red seaweed. *Journal of Cleaner Production*, *259*, 120836.
Kornprobst, J.-M. (2005). *Substances Naturelles D'origine Marine*. Paris: Tech et Doc Lavoisier.
Kraan, S. (2013). Mass-cultivation of carbohydrate rich macroalgae, a possible solution for sustainable biofuel production. *Mitigation and Adaptation Strategies for Global Change*, *18*(1), 27–46.
Kraan, S. (2020). Seaweed resources, collection, and cultivation with respect to sustainability. In *Sustainable seaweed technologies* (pp. 89–102). London: Elsevier.
Krause-Jensen, D., Lavery, P., Serrano, O., Marba, N., Masque, P., & Duarte, C. M. (2018). Sequestration of macroalgal carbon: The elephant in the Blue Carbon room. *Biology Letters*, *14*, 20180236.
Krishnan, M, & Narayanakumar, R. (2010). Structure, conduct and performance of value chain in seaweed farming in India. *Agricultural Economics Research Review*, *23*, 505–514.
Lakner, C., Gerszon Mahler, D., Negre, M., & Prydz, E.B. (2020). How much does reducing inequality matter for global poverty? *Global poverty monitoring technical note 13*.
Lalegerie, F., Gager, L., Stiger-Pouvreau, V., & Connan, S. (2020). The stressful life of red and brown seaweeds on the temperate intertidal zone: Effect of abiotic and biotic parameters on the physiology of macroalgae and content variability of particular metabolites. In N. Bourgougnon, & J. P. Jacquot (Eds.), *Vol. 95. Seaweeds around the world: State of art and perspectives. Advances botanical research*. London: Elsevier.
Lavers, J. L., Dicks, L., Dicks, M. R., & Fin, A. (2019). Significant plastic accumulation on the Cocos (Keeling) Islands, Australia. *Scientific Reports*, *9*, 7102.
Leandro, A., Pereira, L., & Gonçalves, A. M. (2020). Diverse applications of marine macroalgae. *Marine Drugs*, *18*, 17.
Lebreton, L., Slat, B., Ferrari, F., Sainte-Rose, B., Aitken, J., Marthouse, R., et al. (2018). Evidence that the Great Pacific Garbage Patch is rapidly accumulating plastic. *Scientific Reports*, *8*, 4666.
Lehahn, Y., Ingle, K. N., & Golberg, A. (2016). Global potential of offshore and shallow waters macroalgal biorefineries to provide for food, chemicals and energy: Feasibility and sustainability. *Algal Research*, *17*, 150–160.
Lehmann, A. (2020). *Des services écosystémiques au développement durable. Lecture Webinar on May 7th 2020 organized by Rovaltain Foundation*.
Leliaert, F., Smith, D., Moreau, H., Herron, M., Verbruggen, H., Delwiche, C., et al. (2012). Phylogeny and molecular evolution of the green algae. *Critical Reviews in Plant Sciences*, *31*, 11–46.
Levine, I. (2016). Algae: a way of life and health. In J. Fleurence, & I. Levine (Eds.), *Seaweed in health and disease prevention*. Amsterdam Boston Heidelberg London: Elsevier, Academic Press.
Levine, I., & Fleurence, J. (2018). In J. Fleurence, & I. Levine (Eds.), *Microalgae in health and disease prevention*. Amsterdam Boston Heidelberg London: Elsevier, Academic Press.

Lloyd's Register Foundation. (2020). *Seaweed revolution: A manifesto for a sustainable future*. Rapport.
Mac Monagail, M., Cornish, L., Morrison, L., Araújo, R., & Critchley, A. T. (2017). Sustainable harvesting of wild seaweed resources. *European Journal of Phycology*, *524*, 371–390.
MacArtain, P., Gill, C. I., Brooks, M., Campbell, R., & Rowland, I. R. (2007). Nutritional value of edible seaweeds. *Nutrition Reviews*, *65*, 535–543.
Machado, L., Tomkins, N., Magnusson, M., Midgley, D. J., de Nys, R., & Rosewarne, C. P. (2018). In vitro response of rumen microbiota to the antimethanogenic red macroalga *Asparagopsis taxiformis*. *Microbial Ecology*, *75*, 811–818.
Magnussona, M., Glassona, C. R. K., Matthew Vuckob, J., Angellb, A., Neohb, T. L., & de Nys, R. (2019). Enrichment processes for the production of high-protein feed from the green seaweed *Ulva ohnoi*. *Algal Research*, *41*, 101555.
Marzinelli, E. M., Leong, M. R., Campbell, A. H., Steinberg, P. D., & Vergés, A. (2016). Does restoration of a habitat-forming seaweed restore associated faunal diversity? *Restoration Ecology*, *24*, 81–90. https://doi.org/10.1111/rec.12292.
Merci Les Algues. (2020). https://mercilesalgues.com/ (online on July 7th 2020).
Millennium Ecosystem Assessment. (2005). *Ecosystems and human well-being: Synthesis*. Washington, DC: Island Press.
Msuya, F. E., & Hurtado, AQ. (2017). The role of women in seaweed aquaculture in the Western Indian Ocean and South-East Asia. *European Journal of Phycology*, *52*, 482–494. https://doi.org/10.1080/09670262.2017.1357084.
Nešic, A., Cabrera-Barjas, G., Dimitrijevic-Brankovic, S., Davidović, S., Radovanović, N., & Delattre, C. (2019). Prospect of polysaccharide-based materials as advanced food packaging. *Molecules*, *25*, 135.
NETALGAE. (2012). *Overview of the seaweed industry by country: Ireland, France, Norway, Portugal, Spain, United Kingdom, An output of the Netalgae project—Interreg IVB* (p. 8).
Niklas, K. J., & Kutschera, U. (2010). The evolution of the land plant life cycle. *New Phytologist*, *185*, 27–41.
Okoli, C. H., Adams, T. A., Brigljević, B., & Liu, J. L. (2016). Design and economic analysis of a macroalgae-to-butanol process via a thermochemical route. *Energy Conversion and Management*, *123*, 410–422.
Parc Naturel Marin Iroise. (2018). *Retour sur le conseil de gestion du Parc naturel marin d'Iroise*. Press release in November 2018 au Conquet, France.
Peñuela, A., Robledo, D., Bourgougnon, N., Bedoux, G., Hernández-Núñez, E., Freile-Pelegrín, Y., et al. (2018). Environmentally friendly valorization of *Solieria filiformis* (Gigartinales, Rhodophyta) from IMTA using a biorefinery concept. *Marine Drugs*, *16*, 487.
Pérez-Lloréns, J. L., Mouritsen, O. G., Rhatigan, P., Cornish, M. L., & Critchley, A. T. (2020). Seaweeds in mythology, folklore, poetry, and life. *Journal of Applied Phycology*, *32*, 3157–3182.
Placencia Seaweed Farmers. (2016). *Placencia SeaWeed Project Shamax Production*. https://www.youtube.com/watch?v=Tzusmxs8Jh8&feature=youtu.be.
Prabhu, M., Chemodanov, A., Gottlieb, R., Kazir, M., Nahord, O., Gozin, M., et al. (2019). Starch from the sea: The green macroalga *Ulva ohnoi* as a potential source for sustainable starch production in the marine biorefinery. *Algal Research*, *37*, 215.
Pyšek, P., Hulme, P. E., Simberloff, D., Bacher, S., Blackburn, T. M., Carlton, J. T., et al. (2020). Scientists' warning on invasive alien species. *Biological Reviews*, *95*(6), 1511–1534. brv.12627.
Ramasubramani, R., Praveen, R., & Sathyanarayanan, K. S. (2016). Study on the strength properties of marine algae concrete. *Rasayan Journal of Chemistry*, *9*, 706–715.

Rebours, C., Marinho-Soriano, E., Zertuche-González, J. A., Hayashi, L., Vásquez, J. A., Kradolfer, P., et al. (2014). Seaweeds: An opportunity for wealth and sustainable livelihood for coastal communities. *Journal of Applied Phycology*, *26*, 1939–1951.

Rinaudo, M. (2008). Main properties and current applications of some polysaccharides as biomaterials. *Polymer International*, *57*, 397–430.

Rioux, L. E., Beaulieu, L., & Turgeon, S. L. (2017). Seaweeds: A traditional ingredients for new gastronomic sensation. *Food Hydrocolloids*, *68*, 255–265.

Ripple, W. J., Wolf, C., Newsome, T. M., Galetti, M., Alamgir, M., Crist, E., et al. (2017). World scientists' warning to humanity: A second notice. *Bioscience*, *67*, 1026–1028.

Rochman, C. M., Akbar Tahir, S., Williams, L., Baxa, D. V., Lam, R., Miller, J. T., et al. (2015). Anthropogenic debris in seafood: Plastic debris and fibers from textiles in fish and bivalves sold for human consumption. *Plastic Science Report*, *5*, 14340.

Roque, B. M., Brooke, C. G., Ladau, J., Polley, T., Marsh, L. J., Najafi, N., et al. (2019). Effect of the macroalgae Asparagopsis taxiformis on methane production and rumen microbiome assemblage. *Animal Microbiome*, *1*, 1–14.

Rosa, G. P., Tavares, W. R., Sousa, P. M. C., Pagès, A. K., Seca, A. M. L., & Pinto, D. C. G. A. (2019). Seaweed secondary metabolites with beneficial health E effects: An overview of successes in *in vivo studies and clinical trials*. *Marine Drugs*, *18*, 2–35.

Rupérez, P. (2002). Mineral content of edible marine seaweeds. *Food Chemistry*, *79*, 23–26.

Schaeffer, D. J., & Krylov, V. S. (2000). Anti-HIV activity of extracts and compounds from algae and cyanobacteria. *Ecotoxicology and Environmental Safety*, *45*, 208–227.

Sedrati, M. (2018). A sustainable alternative for coastal dune restoration by sand-trapping fences and algae wrack: AlgoBox®. In *20th EGU General Assembly, EGU2018, Proceedings from the conference held 4-13 April, 2018 in Vienna, Austria* (p. 7376).

Sedrati, M., & Cochet, J. (2015). AlgoBox®: Un outil écologique pour la régénération des pieds de dunes grâce aux échouages de macro-algues. In *Coastal and maritime Mediterranean conference*. available online http://www.paralia.fr.

Singh, V., Tiwari, A., & Das, M. (2016). Phyco-remediation of industrial waste-water and flue gases with algal-diesel engenderment from micro-algae: A review. *Fuel*, *173*, 90–97.

Skjermo, J., Marie Aasen, I., Forbord, S., Solbakken, R., Steinhovden, K. B., Handå Co-authors, A., et al. (2014). A new Norwegian bioeconomy based on cultivation and processing of seaweeds: Opportunities and R&D needs. In *SINTEF fisheries and aquaculture SINTEF fisheries and aquaculture*. In undefined www.sintef.no/fisk.

Smetacek, V., & Zingone, A. (2013). Green and golden seaweed tides on the rise. *Nature Publishing Group*, *504*(7478), 84–88. https://doi.org/10.1038/nature12860.

Sørensen, P., & Møller, W. F. (2008). Place and climate. In T. Dahl (Ed.), *Climate and architecture*. London, New York: Taylor & Francis.

Stengel, D. B., Connan, S., & Popper, Z. A. (2011). Algal chemodiversity and bioactivity: Sources of natural variability and implications for commercial application. *Biotechnology Advances*, *29*, 483–501.

Stévant, P., Rebours, C., & Chapman, A. (2017). Seaweed aquaculture in Norway: Recent industrial developments and future perspectives. *Aquaculture International*, *25*(4), 1373–1390. https://doi.org/10.1007/s10499-017-0120-7.

Suganya, T., Varman, M., Masjuki, H. H., & Renganathan, S. (2016). Macroalgae and microalgae as a potential source for commercial applications along with biofuels production: A biorefinery approach. *Renewable and Sustainable Energy Reviews*, *55*, 909–941.

Sully, S., Burkepile, D. E., Donovan, M. K., Hodgson, G., & van Woesik, R. (2019). A global analysis of coral bleaching over the past two decades. *Nature Communications*, *10*, 1–5.

Susilorinia, R., Rr, M. I., Hardjasaputrab, H., Tudjonoc, S., Hapsaria, G., Wahyu Sa, R., et al. (2014). The advantage of natural polymer modified mortar with seaweed:green

construction material innovation for sustainable concrete. In *Vol. 95. 2nd international conference on sustainable civil engineering structures and construction materials (SCESCM 2014). Procedia engineering* (pp. 419–425).
Suyo, J. G. B., Masson, V. L., Shaxson, L., & Luhan, M. R. J. (2020). A social network analysis of the Philippine seaweed farming industry: Unravelling the web. *Marine Policy*, *118*, 104007. https://doi.org/10.1016/j.marpol.2020.104007.
Taylor, G. (2008). Biofuels and the biorefinery concept. *Energy Policy*, *36*, 4406–4409.
Terme, N., Chénais, B., Fournière, M., Bourgougnon, N., & Bedoux, G. (2019). Chapter 15: Algal derived functional lipids and their role in promoting health recent advancements. In *Micro and macroalgal processing: food and health perspectives* Wiley.
Thomas, N. V., & Kim, S. K. (2011). Potential pharmacological applications of polyphenolic derivatives from marine brown algae. *Envrionmental Toxicology and Pharmacology*, *32*, 325–335.
Tirichine, L., & Bowler, C. (2011). Decoding algal genomes: Tracing back the history of photosynthetic life on Earth. The plant genome: An evolutionary view on structure and function. *The Plant Journal*, *66*, 45–57.
Trivedi, J., Aila, M., Bangwal, D. P., Kaul, S., & Garg, M. O. (2015). Algae based biorefinery—How to make sense? In *vol. 47. Renewable and sustainable energy reviews* (pp. 295–307). Elsevier Ltd.
United Nations. (2020a). *UN comtrade*. http://comtrade.un.org. accessed on 25 April 2020.
United Nations. (2020b). *Sustainable consumption and production. Topics*. https://sdgs.un.org/topics/sustainable-consumption-and-production-76 (online on July 18th 2020).
Urban, M. C. (2015). Accelerating extinction risk from climate change. *Sciences*, *348*, 571–573.
Valderrama, D., Cai, J., Hishamunda, N., & Ridler, N. (Eds.). (2013). *Social and economic dimensions of carrageenan seaweed farming. Fisheries and aquaculture technical paper no.* Rome, Italy: FAO.
Van Der Wal, H., Sperber, B. L. H. M., Houweling-tan, B., Bakker, R. R. C., Brandenburg, W., & López-contreras, A. M. (2013). Production of acetone, butanol, and ethanol from biomass of the green seaweed *Ulva lactuca*. *Bioresource Technology*, *128*, 431–437.
Wang, H. M. D., Chen, C. C., Huynh, P., & Chang, J. S. (2015). Exploring the potential of using algae in cosmetics. *Bioresource Technology*, *184*, 355–362.
Watanuki, A., Aota, T., Otsuka, E., Kawai, T., Iwahashi, Y., Kuwahara, H., et al. (2010). Restoration of kelp beds on an urchin barren: Removal of sea urchins by citizen divers in southwestern Hokkaido. *Bulletin of Fisheries Research Agency*, *32*, 83–87.
Wells, M. L., Potin, P., Craigie, J. S., Raven, J. A., Merchant, S. S., Helliwell, K. E., et al. (2017). Algae as nutritional and functional food sources: Revisiting our understanding. *Journal of Applied Phycology*, *29*, 949–982.
Whitmee, S., Haines, A., Beyrer, C., et al. (2015). Safeguarding human health in the Anthropocene epoch: Report of The Rockefeller Foundation–Lancet Commission on planetary health. Lancet. Published online July 16. https://doi.org/10.1016/S0140-6736(15)60901-1.
Widera, B. (2014). Possible application of seaweed as building material in the modern seaweed house on Læsø. In *30th international plea conference 16-18 December 2014* CEPT University.
World Bank. (2018). *India's seaweed squads boost women's incomes and confidence*. http://wrld.bg/5bOb30koDqZ.