



Saved by seaweeds: phyconomic contributions in times of crises

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Received: 25 June 2020 / Revised and accepted: 10 September 2020 / Published online: 7 November 2020

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Abstract

Seaweeds (macroalgae) are, together with microalgae, main contributors to the Earth's production of organic matter and atmospheric oxygen as well as fixation of carbon dioxide. In addition, they contain a bounty of fibres and minerals, as well as macro- and micronutrients that can serve both technical and medicinal purposes, as well as be a healthy and nutritious food for humans and animals. It is therefore natural that seaweeds and humans have had a myriad of interwoven relationships both on evolutionary timescales as well as in recent millennia and centuries all the way into the Anthropocene. It is no wonder that seaweeds have also entered and served as a saviour for humankind around the globe in many periods of severe needs and crises. Indeed, they have sometimes been the last resort, be it during times of famine, warfare, outbreak of diseases, nuclear accidents, or as components of securing the fabric of social stability. The present topical review presents testimony from the history of human interaction with seaweeds to the way humankind has, over and over again, been 'saved by seaweeds'. It remains a historical fact that in extreme conditions, such as shortage and wars, humans have turned to seaweeds in times of 'needs must' and created new opportunities for their uses in order to mitigate disasters. Lessons to be learned from this history can be used as reminders and inspiration, and as a guide as how to turn to seaweeds in current and inevitable, future times of crises, not least for the present needs of how to deal with changing climates and the pressing challenges of sustainable and healthy eating.

Keywords Seaweeds · Crisis · War · Famine · Nuclear accidents · Human diseases · Unemployment

Introduction: seaweeds and humankind

Seaweeds are macroalgae that constitute a very heterogeneous and diverse group of multicellular organisms. Being photosynthetic, seaweeds together with the microalgae are responsible for producing most of the atmosphere's oxygen and fixing most of the carbon dioxide (Chapman 2013). Comprising more than 12,000 species, seaweeds are found in all climatic zones on the planet and they can be harvested sustainably in the wild and/or farmed by (mari)aquaculture using various

phyconomic practices. Considering the omnipresence of seaweeds in coastal areas, it is maybe not surprising that these organisms have played an important role for life on the planet, not least human beings during evolutionary time scales, as well the present times.

It is now believed that our close ancestors, *Homo erectus*, evolved near aqueous basins and not on the hot African grasslands (Crawford and Marsh 1989; Cunnane et al. 2014). Apart from archaeological finds, a strong argument for the human lineage evolving near shores of big lakes or oceans is that it

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was only here that they would find enough food supplies with the necessary and sufficient amounts of the essential, nutritional building blocks that are the prerequisite for building a complex neural system and a brain with the very large brain/body weight ratio (2.1%) that is a singular characteristic of humans (Cunnane et al. 2014). In particular, these building blocks were essential fatty acids, the super-unsaturated omega-3 and omega-6 fatty acids, as well as a range of micronutrients, such as iodine, iron, copper, zinc and selenium (Cornish et al. 2017). Indeed, it is the algae, not animals, fungi or plants, that uniquely possess the necessary enzyme systems required to synthesize large amounts of super-unsaturated fatty acids. This is where algae came into the picture and entered an essential entanglement with human evolution towards today's *Homo sapiens*.

Since that time, humans have directly or indirectly depended on algae, including seaweeds. First as a food source, most prominently manifested along the 'kelp highway' leading to the peopling of the Americas (Erlandson et al. 2007), later also as a useful building material (Mouritsen 2013), feed for livestock (Rajauia 2015), and medicinal aids (Fleurence and Levine 2016), as well as a range of modern-time technical applications (Pérez-Lloréns et al. 2018). In some parts of the world, the tradition for using seaweeds as a valuable food has been maintained until present times (Mouritsen 2013; O'Connor 2017; Pérez-Lloréns et al. 2018), whereas in other places, this use was seemingly forgotten, and seaweeds have mostly served as various raw materials for a number of practical uses and extracts—many times in distanced ways where most people would not know that a specific application was actually based on a particular type of seaweed, e.g. as a food ingredient, a hydrogel, a medicinal aid or a fire repellent.

Moreover, the close relationships between seaweeds and human beings can also be seen to be reflected in a rich culture, mythology, folklore and poetry (O'Connor 2017; Pérez-Lloréns et al. 2020). Importantly in the present context, humankind and human societies have time and time again turned to seaweeds in times of crises to take advantage of what this diverse and ancient, polyphyletic assemblage of marine, photosynthetic organisms can offer in order to meet the basic needs of sustenance, alleviate suffering from diseases, and secure health, well-being, and survival at critical stages of human history. With the severe scale of global problems that humans and societies now face with pandemics, climate change and the need for sustainable food sources and supplies, we may once again turn our collective and focused attention to seaweeds.

Seaweeds during times of famine and hardship

— "They [the Irish] were starving, eating old cabbage leaves, roadside weeds, rotten turnips, while on the coast

itself the population lived on *dillisk* (dulse) and raw limpets". (Woodham-Smith 1962)

— "Potatoes, children, seaweeds": an old Irish aphorism about women's preferences reveal the importance of seaweed in daily life.

Various specific seaweeds have been an important part of the diet in many Eastern countries for millennia, but only sparsely exploited and eaten in the Western world. However, it did not always use to be like that, and coastal dwellers and communities have to some extent used seaweeds as food/feed both for themselves and their livestock (Sauvageau 1920; Mouritsen 2013; O'Connor 2017; Pérez-Lloréns et al. 2018). Ironically, in contrast to the veneration of seaweeds and their benefits in Eastern countries, those seaweeds in Europe have unfortunately been branded as being associated with poor people and famine.

Ireland is an interesting example in this connection. Harvesting seaweeds is a long-standing tradition there. The farmers, sheep farmers and fishers with their lands adjoining the coast have for hundreds of years enjoyed the rights to harvest the seaweeds of the foreshore and intertidal zone in order to feed themselves and their domestic animals and also to build organic materials and soil as well as fertilize their plots of land and in particular their potato beds. In spite of the long tradition of exploiting marine algae in Ireland (Guiry and Morrison 2013), most people, unfortunately, presently associate them with poverty and the starvation resulting from the Great Famine that devastated the country in 1845–1849 (Woodham-Smith 1962; Gallagher 1982).

The poor population in the western part of Ireland was at that time completely dependent on their crop of potatoes, which taken together with dairy were nutritionally adequate for living. An Irish peasant would in the middle of the nineteenth century consume 3–5 kg of potatoes every day. When the potato blight hit at the end of the 1840s, disaster was imminent. Sadly, about one million died during the Great Famine. As a direct consequence, from 1848 to 1950, more than 6 million Irish men and women emigrated, and the population declined from 4.4 million in 1861 to 2.8 million in 1961. During the famine, access to the foreshore with a rich vegetation of nutritionally dense seaweeds became the 'last resort' for the starving population—so it is no wonder why seaweeds later became associated with the troubled time of famine and as the poor people's food.

The relation between poor coastal Irish populations and seaweeds is beautifully reflected in the novel *Trinity* (Uris 1976) and in Robert J. Flaherty's *Man of Aran* ethno-fiction documentary (1934) which chronicled the daily life of the inhabitants of these islands on the west coast of Ireland. It showed the struggle for survival of a family of islanders and the harshness of their work on the coast. In order to grow just a few potatoes, they had to gouge out holes in the rock and fill

them with the little soil they were able to find. This was then supplemented with the seaweeds transported by the women in large baskets on their backs (Fig. 1). This story was then glamorised in the Hollywood movie *The Field*.

The revival of the Irish seaweed cuisine for purposes of health and pleasure has since been described by Prannie Rhatigan (Rhatigan 2009, 2018).

Brown seaweeds (kelp) contain large amounts of iodine (Teas et al. 2004). This precious compound that could be used as an antiseptic and ointment, as well as source for silver iodide for photographic plates, was the basis for a cottage industry at the Irish coast providing a little extra and welcome source of income for the poor. Seaweeds were dried and burned into ashes from which both iodine and potash for glass production could be recovered. Harper (2014) writes that a new suit or frock worn to church in Carnlough in western Ireland brought the remark, 'The kelp is shining on you'.

Similarly, in Iceland, when food was in short supply and there was a risk of famine, the Icelanders probably resorted to species that were hardier than the dulse (*Palmaria palmata*) they would more commonly consume (Kristjánsson 1980). The most probable candidates were carrageen (*Chondrus crispus*) and winged kelp (*Alaria esculenta*), which were normally used only for animal fodder. The consumption of seaweeds was, however, for many centuries linked mostly to times of hardship. On the Faroe Islands, there is even a saying about a person who dies in poverty: 'He was laid in his grave with a piece of seaweed in his mouth' (Mouritsen 2013).

The dwellers of some coastal regions in South America have also consumed seaweeds during periods of scarcity. For instance, macocco (*Gigartina* spp.) is typical of Peru, and luche (*Pyropia columbina*) and cochayuyo (*Durvillaea antarctica*) have been consumed in Chile since pre-Columbian times (Pérez-Lloréns et al. 2018). The first record of seaweed used by man for food and/or medicine was found in Monte Verde (Chile) going 14,000 years back (Dillehay



Fig. 1 Poor families collecting seaweeds at the West Coast of Ireland during the Great Famine, 1845–1849

et al. 2008). Seaweeds may yet again in this region come to poor people's rescue and cochayuyo is promoted to combat hunger in poor areas in southern Chile (Milesi 2018).

Seaweeds during times of war and international conflicts

With their many exceptional and unique material properties and chemical components, seaweeds have not surprisingly come to rescue during times of warfare. An example from Antiquity describes how Muslim scientists and naval commanders in the early eighth century found a way to use seaweed to avoid damage to their vessels from the devastating so-called Greek Fire that the Byzantine fleet used in order to put enemy vessels on fire (Fig. 2). An Alexandrian 'Abd al-Rahmān understood how to extract a material called algin from the brown alga *Cystoseira barbata* which he then used to fireproof cloth. He used this cloth to cover the ships protecting them from the Greek Fire (Khalilieh and Boulos 2006).

During WW1 and WW2, many materials for technical applications were in short supply, and in some cases, the available biomass from natural populations of various seaweeds provided a temporary rescue for manufacturing of hydrogels and fine chemicals. Indeed, seaweed extract for the benefit of plant production is at least in part attributed to the use of liquid seaweed extracts as a darkening agent for camouflage netting. It was 'water soluble' so in the rain it dropped off and was found to enhance growth or plants around the points of use (Craigie 2011).

During WW1, the Californian kelp industry manufactured large quantities of potassium chloride, iodine and acetone as well as ethyl acetate, ethyl propionate, ethyl butyrate and 'kelpchar' (a decolorizing carbon of exceptional quality) (Sanford 1958; Woodward 1965). Extracts from *Laminaria* species were used to seal grenades. Alginic acid was used as a binder in the manufacture of cartridge primers, and extracts from available red seaweeds were used to replace foreign gums that were in short supply (Chapman 1950). Germany



Fig. 2 A Byzantine ship uses Greek Fire against a ship of the rebel. Twelfth century illustration from the Madrid Skylitzes. (Public Domain) (<https://bit.ly/30TwEKM>)

placed an embargo on the import of potash to the USA, and in order to have enough for gun powder production, the Californian kelp forests were able to provide materials to produce this indispensable component (Neushul 1989) (Fig. 3).

The carrageenans extracted from the red seaweed *Chondrus crispus* (Irish moss) were used during WW1 to disguise the bitter taste of some medicines and as sore throat relievers for soldiers who had been gassed (Kreig 1966).

During WW2, alginates were also used to produce camouflage paint and artificial silk material for parachutes (Long 2014). Agar was one of the strategic materials, owing to certain of its unique gel-forming properties that allowed its use in the preparation of solid culture media in bacteriology (Sanford 1958). In many countries, there was a shortage of agar, mostly because its supply from Japan was cut off. This stimulated a

development of using local seaweeds to produce related polysaccharides for hydrogels. In New Zealand, girls were encouraged by the local newspaper (Auckland Star 1942) to collect ‘the right seaweed’ to produce agar for the hospitals. A similar turning to local seaweeds took place in Denmark right after the war where a shortage of imported agar enabled a whole new industry springing up to produce what was termed Danish agar derived from the red seaweed called ‘black carrageen’, *Furcellaria lumbricalis/fastigiata* (due to its colour when dried) (Breinholst 1963). Today, this might be referred to as ‘disruptive technology’ but is an indication of phyconomic ingenuity spurred on by needs. Black carrageen contains furcelleran that is a polysaccharide having properties similar to, but not quite exactly the same as, agar. The production went on from 1946 to 1960 and led to the development of

Fig. 3 The Hercules Powder Company in Southern California (South Bay Historical Society) which harvested kelp to produce potash to manufacture gun powder during WW1. (CC BY 2.0) (<https://bit.ly/2AGryXM>)

The Literary Digest for December 21, 1918 51

HERCULES POWDER CO.

From War to Peace

TO satisfy the demands of war the Hercules Powder Company has cut over 621,000 tons of kelp in the Pacific Ocean during the last two-and-a-half years. This has been converted into chemicals necessary to the manufacture of smokeless powder, black powder, shell lacquers, and coating for aeroplane wings. Over \$5,000,000 have been expended in the great plant at San Diego, Cal., in which the chemicals are extracted from this giant seaweed.

The development of a new source of these chemicals—potash, acetone, and other solvents—was vital to the triumph of democracy. Now that victory is assured, these and others are at the disposal of the industries of peace.

Kelp yields many useful products in addition to those which have been necessary to the prosecution of the war. Many of them are well-known to the drug and chemical trades. Some of them have never been produced in commercial quantities before. Others that are now made only on a laboratory scale can be readily turned out in quantity if a demand is found.

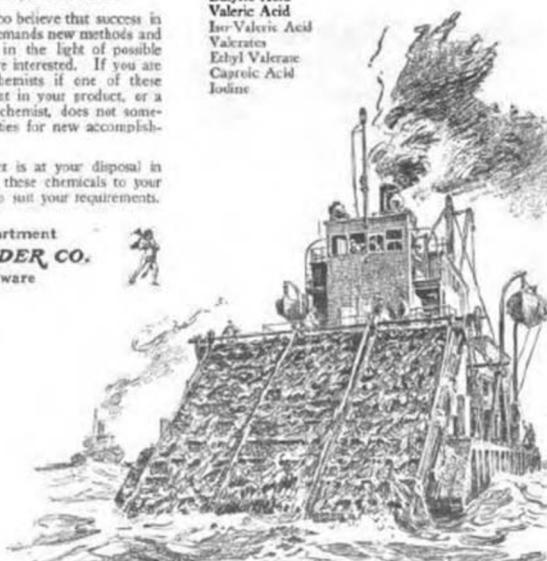
We ask all manufacturers and chemists who believe that success in the new industrial era which is upon us demands new methods and new ideas, to consider these chemicals in the light of possible applications to processes in which they are interested. If you are such a manufacturer, ask your chief chemists if one of these materials does not suggest an improvement in your product, or a saving in its manufacture. If you are a chemist, does not something in the list at the right offer possibilities for new accomplishments in your profession?

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Valrates
Ethyl Valerate
Caproic Acid
Iodine



the company called Copenhagen Pectin, with exports to other parts of Europe and the USA to be used in food and textile industries. It was so successful that the activities basically wiped out the Danish populations of *Furcellaria*. Today, the economic utilisation of this genus of seaweed is limited to some Baltic states and Eastern Canada (Prince Edward Island).

The WW2 medic Major George Blaine was the first clinician to investigate the interaction of wound tissue with alginates, and to realize their potential as absorbers of exudate. He used them on burn wounds in the Far East and carried out clinical studies when the war was over (Blaine 1946). The scarcity of food during WW2 raised people's interest in seaweeds as food. German occupation troops in Norway built two bakeries to make seaweed bread (Schwimmer 1955). An amusing instance of confusing a cryptogamist for a cryptogramist led to the recruitment of the seaweed expert Geoffrey Tandy to work on the secret WW2 project in Britain to crack the code of the German Naval Enigma machine whereby a seaweed scientist so to speak helped win the war (Freeborn 2014).

Seaweeds and nuclear accident

As mentioned above, some seaweeds contain substantial amounts of iodine (Teas et al. 2004), in particular brown seaweeds of the Laminariales (Mouritsen et al. 2019a). Iodine from the diet accumulates in the thyroid and is essential for its healthy functioning. This observation renders certain seaweeds a useful source for iodine, and consumption of marine food for iodine supply has at times been critical for large populations around the world (Mouritsen 2013) (Fig. 4). The thyroid gland of a normal adult contains in steady-state of approximately 8 mg of iodine, of which ca. 1–2 µg per kilogram of body weight is utilized each day. For a person weighing 75 kg, this translates into a daily requirement of



Fig. 4 Burning of kelp at the coast of Northern Brittany. The ashes contained various salts like potash and iodine from the brown seaweeds

150 µg of iodine which must be ingested with food and drink. The daily requirement can be greater if that iodine is displaced by other substances, especially chlorine, which is added to drinking water in some places.

Accumulation of iodine in the thyroid can cause a critical problem if it is replaced by the radioactive isotope iodine-131. This isotope has been released accidentally by nuclear power plants and/or used in various forms of radiotherapy. Iodine-131 accumulates in the thyroid and later in the reproductive organs. Human consumption of iodine tablets, or iodine derived from brown seaweeds, can help to reduce the uptake of radioactive iodine by the thyroid gland via displacement of the radioactive isotope due to a surplus of the common isotope iodine-127. Iodine supplements constitute an essential part of the protection against radiation poisoning that could result from an accident at a nuclear plant or in conjunction with the explosion of a nuclear weapon. Evidence of uses for seaweeds in such critical situations, used as a prophylactic measure, can be traced to increased sales of kelp products following the disasters at the Chernobyl (in 1986) and Fukushima (in 2011) nuclear power plants (Braverman et al. 2014). Preparing the necessary stocks for iodine-131 emergencies is also relevant for managing terrorism, accidental nuclear errors and ultimately nuclear warfare (Braverman et al. 2014).

Seaweeds and livelihood in developing countries

Many developing countries and particularly their coastal regions suffer from unemployment and societal structures which make it very difficult for families to arrange for their daily needs. In many cases, looking after the family (health, welfare, education, etc.) and especially the children is left to women. There are examples where particular types of seaweeds have come to rescue to these women and played a pivotal socio-economic role in the survival of their families. In small, family-owned businesses, women engage in seaweed aquaculture particularly of *Kappaphycus* spp. and *Eucheuma* spp. in the Western Indian Ocean and South-East Asia, including Africa, India and South-east Asia. Many more women than men are involved in the farming of seaweeds in shallow, intertidal basins. These 'seaweed women' have made significant phyconomic advances in the sustainability of seaweed farming for more than four decades and their dedication, patience and resilience illustrate tenacity in the face of crises (Bay-Larsen et al. 2014; Periyasamy et al. 2014; Msuya and Hurtado 2017; Hurtado et al. 2019).

As a specific example, in Zanzibar, many women support their families entirely by farming algae on strings in shallow waters (Forsberg and Vestling 2018). Women produced 412 t of seaweed in the year 2016/17 which was equivalent to 80% of the total seaweed production in Zanzibar whereas men

produced only 103 t equivalent to 20% of the total production. The income from selling the crop to the carrageenan companies improves the livelihood of the families and helps to pay school fees for their children during the year (Kalumanga 2018). Recently, changing climate has worsened the conditions for seaweed farming and hence eroded women's status in Zanzibar (Ott 2018). In Malaysia, governmental capacity building programmes have been set up to improve skills and knowledge among local seaweed cultivators, in particular women, in order stimulate rural community development (Kunjuraman et al. 2019). Coastal and sustainable livelihood through seaweed mariculture has also been valued in Indonesia (Aslan et al. 2018; Waters et al. 2019). It should however be remarked that due to cultural differences in tradition for what kind of work men and women traditionally engage in, there are differences in the way family farming is done in different regions (Fig. 5).

Seaweeds, human health and disease prevention

Medicinal uses of seaweeds, as well as potential health benefits of consuming seaweeds, or seaweed-derived products



Fig. 5 Women cultivate Spinosum (*Eucheuma denticulatum*) in Zanzibar for carrageenan production. Courtesy of Marie Frost

have been extensively reviewed in the scientific literature and are indicative of their importance and growing applications, both in general (Fleurence and Levine 2016; Délérès et al. 2016), as well as in specific cases, such as heart- and coronary diseases (Cornish et al. 2015; Cardoso et al. 2015; Murai et al. 2019), brain and neural development and diseases (Cornish et al. 2017; Guo et al. 2019; Schepers et al. 2020; Hannan et al. 2020), irritable bowel syndrome and the human microbiome (Mathieu et al. 2018; Cornish et al. 2019), prevention and treatment of various cancers (Mamvar et al. 2013; Jiang and Shi 2018), viral infections (Domínguez 2013; Mazalovska and Kouokam 2018), and parasite infections (Shafiq et al. 2018), as well as diabetes and obesity (Sharifuddin et al. 2015; Husni 2018; Attjioui et al. 2020; Bermanoa et al. 2020). Furthermore, various bioactive compounds of seaweed origin, such as secondary metabolites (Holdt and Kraan 2011; Kim 2012; Collins et al. 2016; Rosa et al. 2020), nutraceuticals (Domínguez 2013; Shannon and Abu-Ghannam 2019) and other functional ingredients (Peñalver et al. 2020), have been suggested for judicious use as prophylactics and interventions in disease prevention. Recently, it has been pointed out that seaweeds with their many bioactive compounds should be considered as a rescue to cure the so-called forgotten diseases, not least tropical deceases, that are pestering 1.4 billion people in the poorest parts of the world, such as insect-borne infections, leishmaniasis, helminth infections and trypanosomiasis (Shafiq et al. 2018; Falkenberg et al. 2019; Freile-Pelegrín and Tasdemir 2019).

Important elements discovered in the ashes of brown seaweeds, such as bromine by Balard in 1826 (Smith 1926) and prior to that the discovery of iodine by Courtois in 1811, were very early considered as pharmaceuticals and used for treatments in various medical applications. Bromine has recently been identified as an essential trace element for humans (McCall et al. 2014), and the bromide salts were once a major medical sedative before replacement by shorter acting drugs. Iodine, of course, is well known to be an essential nutrient, important for thyroid health and cognitive aptitude (Zimmermann 2009). It furthermore plays a role in antisepsis and wound management (Selvaggi et al. 2003). Globally, iodine deficiency is the greatest preventable cause of mental impairment (WHO 2007), and the opportunity to supplement daily diets with specific seaweeds could have a huge positive impact on the human population (Fig. 6).

In his famous book The Sea (La Mer), the French historian Jules Michelet wrote in 1861 (Michelet 2013):

- For three very sound and sufficient reasons I love and I bless that vast vegetation; small or large, that vegetation has three lovely qualities:
- Firstly, how innocent are all its members: no one of them all is poisonous. Vainly in the whole marine vegetation shall you search for one poisonous plant. Seek in every



Fig. 6 French advertisement praising marine algae as a marine cure for sick children and elderly. (CC BY 4.0) (<https://bit.ly/3dahByZ>)

sea, and in every latitude, you will find the vegetation wholesome, genial, a blessing and a mercy.

- Those innocent plants ask for nothing more than to nourish or to heal animality. Many of them, the laminaires (Laminariales), for instance, contain a luscious sugar; and others, as, for instance, the Corsican or Irish Moss, have a health-restoring bitter; and all, without exception, contain a concentrated and most nourishing mucilage, not a few of them saviours to the weak, worn, perishing lungs of presumptuous and ungrateful man. Where we now exhibit iodine, the English formerly used nothing but a confection of that same Corsican, or Irish, Moss.
- The third characteristic of that vegetation is its marvellous amorousness. We cannot doubt that if we pay the slightest attention to its strange hymeneal metamorphoses, here is the striving to be, beyond being, to be potent beyond power. We see it in the fire flies and the like small things, and we see it no less, if we will only look for it, in the sea weeds which, at the consecrated moment, seem to quit their merely vegetable life and leap into animality.

The utilisation of various seaweeds for their therapeutic and medicinal benefits over the centuries is a testament to their

purported efficacy. Modern medicine, however, has usurped society's reliance on nature for healthcare remedies, and lung infections and other ailments today are treated with the appropriate anti-bacterials or anti-virals. Medicinal plants, including seaweeds, were depended upon to treat many ailments, particularly in coastal communities around the world. One could argue this to be a resource availability situation, rather than a result of actual health benefits, but today, science has validated many of the claims. As an example, in Ireland, a traditional treatment for chest and lung ailments used Irish moss boiled in water or milk, strained and drunk hot (Allen and Hatfield 2004). The alga was also used to treat kidney ailments and burns. These medicinal applications were so valued that a recipe for preparing a demulcent from *Chondrus crispus* 'for diseases of debility' was included in an early *Materia Medica* (Frazer 1864). The relaxing effects of the extracted carrageenans on mucous membranes provided relief in tuberculosis, whooping cough, pneumonia, quinsy and for various gastrointestinal complaints (Fig. 7).

A curious use of seaweed extract has been reported for emergency blood transfusions where the extract has been found to be more effective than sugared water or salt water because the dissolved algal polysaccharides are not broken down in the blood stream (Mathieson 1975).

Growing evidence regarding the influence of the human microbiome on health suggests this will be a new frontier in medical science (Cornish et al. 2019). Seaweeds will also play a role here, but only if appropriate clinical trials are undertaken to follow up on animal trials that have already demonstrated important prebiotic effects (Cherry et al. 2019).

Seaweeds for combating infections and pandemics

Infections from microorganisms and viruses constitute a condition of life for all human beings and most people suffer once, or many times, during the yearly cycle from infections, not least in their airways. The consequences of such infections range from the mild condition of a winter cold to critical cases of life-threatening pneumonia, common influenza and respiratory syndrome corona viral infections such as SARS-CoV and MERS-CoV, including the current pandemic COVID-19 (SARS-CoV-2).

Throughout history, humankind has witnessed global infections leading to massive casualties, virtually wiping out large fractions of the populations (Pereira and Critchley 2020). One of the health conditions that plays a critical role for surviving a serious infection in the lung and the airways is an intact and healthy immune system. A regular diet including judicious consumption of a variety of seaweeds can be a factor which bolsters the immune system (Brown et al. 2014), also



Fig. 7 British advertisement appraising Irish moss (*Chondrus crispus*) for curing infectious diseases like colds and coughs. (Public Domain) (<https://bit.ly/2N7ZoqW>)

by securing gut health and a diverse microbiome (Cornish et al. 2019; Jha et al. 2020).

In the case of the 2020-outbreak of the COVID-19 (SARS-CoV-2) pandemic and the following world economic crisis (Pereira and Critchley 2020), some food manufactures have observed a higher demand for products based on recipes involving seaweed extracts (Food Navigator 2020). This trend exposes the need for more fundamental and clinical research to establish a sound scientific basis for the claim that seaweeds can combat viral infections.

A number of in vitro and in vivo, as well as clinical, studies have established that certain chemical compounds in seaweeds have biological activity in terms of their anti-microbial and anti-viral efficacy, specifically certain peptides. In particular, research has demonstrated broad-spectrum in vitro activity and in vivo efficacy of the anti-viral protein griffithsin (isolated from the red seaweed *Griffithsia* sp.) against emerging viruses of the family Coronaviridae (O'Keefe et al. 2010). Other algal-derived polysaccharides

(e.g. agar, alginate, fucoidan, carrageenan, laminarans, proteo-glycans, galactosyl glycerol and rhamnan sulphate) have in recent years showed some promising potential for combating viral infections and researchers have advocated that the pharmaceutical industry should turn their attention to explore this potential (Ahmadi et al. 2015).

Seaweeds ameliorating changes in climate

It is now recognized by most scientists and politicians that global climate changes are a consequence of anthropogenic activities. These changes involve global warming and more extreme weather conditions, which are accompanied by melting of the ice caps, ocean warming, rising of sea-levels, acidification of the oceans, flooding, droughts and forest fires (Sonali and Kumar 2020). One of the most important reasons for these effects is the dramatic rise in emission of greenhouse gases (GHGs), in particular methane and carbon dioxide. The atmosphere's concentration of carbon dioxide has increased by about 40% since the pre-industrial era. Both with respect to methane and carbon dioxide emissions, seaweeds may come to partial rescue but in very different ways.

Until recently, the contribution of coastal seaweeds and the vast populations of microalgae in the open oceans to the sequestration of global carbon was largely neglected, although already in 1981, Smith (1981) pointed out that marine macrophytes work as a carbon sink. The reason for not taking seaweeds into the calculation of the so-called Blue Carbon-accounting (Blue Economy) was predominantly that seaweeds, in contrast to seagrass-dominated ecosystems, do not deposit carbon near its own rocky habitats (Krause-Jensen and Duarte 2016). Recent work, which also described the sequestering of macroalgal carbon as the 'elephant in the Blue Carbon room', also pointed out that there was compelling evidence that carbon flux from seaweeds accumulated in deep-sea sediments (Krause-Jensen et al. 2018).

The estimated total global export of organic carbon to the ocean has been estimated as 2.4 Pg carbon year⁻¹, of which the autotrophic seaweeds alone contributed to 1.5 Pg carbon year⁻¹, i.e. a very significant fraction (Krause-Jensen et al. 2018). Of this amount, about 0.173 Pg carbon year⁻¹ (i.e. 11%) from seaweeds are potentially sequestered in sediments and deep-sea beds. An outstanding challenge is to trace this flux from the coastal habitats into the deep sea and provide a detailed interpretation of its significance to the global carbon cycle. Although the issue is still somewhat controversial, researchers have also pointed to the importance and adaptation effects of seaweeds due to climate changes, including reduction of wave energy and water flow during storm-flooding, thereby promoting sedimentation, as well as reduction in ocean acidity (for references, see Krause-Jensen et al. 2018).

Obviously, our understanding of the sequestration of carbon by wild resources of seaweed populations, or even enhanced biomass due to phyconomic/aquaculture activities, will not by themselves help to lower carbon dioxide emissions, but they are part of the solution to amelioration of the problems caused. Insightful management of natural resources, as well as increased cultivation of various seaweeds, will have positive effects, although an upper limit for the latter has been estimated at a modest 0.4% of the total seaweed-captured carbon at $0.173 \text{ Pg year}^{-1}$ (Duarte et al. 2017; Laurens et al. 2020) (Fig. 8).

Other ways seaweeds may be used to reduce the footprint of carbon dioxide emissions include replacement strategies for terrestrial food production by seaweed biomass (to be dealt with below) or as a biofuel blend to extend fossil-derived reserves (Chen et al. 2015). It has been estimated that using seaweeds instead of fossil fuel for the production of bioethanol and methane reduces the emission of GHGs by 8%, and even up to 54%, respectively (Fry et al. 2012).

There appear to be two ways in which different seaweeds might help mitigate climate effects caused by ruminant GHG emissions. One is to find more sustainable protein sources so as to replace meat for human consumption (which we will return to later). The other is to reduce the total gas and methane emissions by manipulating the diet of cattle to include seaweeds (Machado et al. 2014; Roque et al. 2019). It is now clear that some seaweeds and their products do indeed lower the emission of methane from ruminant digestion (Kinley and Fredeen 2015). In particular, the red alga *Asparagopsis taxiformis* has shown promising effects. By replacing just 2% of the feed by its dried biomass, it was found that methane was reduced by 70% (Kinley and Vucko 2016) and by 99% with a 5% supplementation of grass feed supplemented with *Asparagopsis* (Machado et al. 2016). At the same time, those cattle ingesting seaweeds were healthier than those feeding on a traditional cattle diet. Hence, emissions of ruminant, enteric fermentation-induced GHG can be reduced significantly by adding various seaweeds to the feed (i.e. this



Fig. 8 On-land aquaculture of seaweeds (*Chondrus crispus*) at Acadian Seaplants, Nova Scotia, Canada

property is not exclusive to *A. taxiformis*). Implementation of these promising results on a large scale is hampered by the limited access to *A. taxiformis* which would require establishment of extensive phyconomic operations. Clearly, further research into the effects of other more commonly available seaweeds is required.

Seaweeds combating pollution

A myriad of seaweeds has shown themselves to serve humankind during critical cases of contamination and pollution in the ocean environment. Two rather different examples provided here demonstrate how the phyconomic enhancement and increased production of selected seaweeds can help mitigate some of the detrimental impacts of human activities on ocean ecosystems.

The first example pertains to the unique capacity of seaweeds for binding metals to their polysaccharides, in particular heavy metals from wastewaters. It has been known for a long time, that in particular brown seaweeds have a capacity for binding metal ions (Bryan 1969). The ability of brown seaweeds to act as a biosorbent for clearing metals in both aqueous environments, as well as soil, is based on the chemical composition and ion-exchange capacity of compounds associated with the cell walls of brown seaweeds, i.e. alginates and fucoidans, with functional groups capable of binding metal ions. Planting of seaweeds in wastewater reservoirs has been implemented in areas of effluent remediation areas (Ortiz-Calderon et al. 2017; Michalak 2020a). Recently, Pennesi et al. (2019) illustrated how the rare metal indium could be recovered from e-waste (old electronic materials), much of which is exported to developing countries where workers (many of whom are children) burn circuit boards to recover precious and rare metals. This causes major health and pollution issues. Biomass of the brown seaweed *Ascophyllum nodosum* was found to help 'mine' in solution the metal indium which is required as an input to new electronics and especially screens (Pennesi et al. 2019).

Particularly since the 'oil crisis' of the 1970s, many authors have suggested that seaweeds could be further exploited as a sustainable source of 'feedstock' for biofuel production (Michalak 2020b, see also below). Related to the issue of removing unwanted toxic elements in seawater is that seaweed forests, present and those developed through inoculation of some form of engineered marine substrata, as in marine ranching (Ohno and Critchley 1993) also helps to clean up the ocean by capturing some of the fertilizer run-off from agricultural and urban areas (Fig. 9).

The second example pertains to using seaweeds in multi-trophic aquaculture for the purpose of nutrient extraction from, e.g. fish farms. As mentioned in the introduction, super-unsaturated fatty acids are a limited resource on the



Fig. 9 The green seaweed *Chaetomorpha linum* sn used as a natural filter in some estuaries from Cádiz Bay, Spain. Courtesy of Juan José Vergara

planet, and due to the negative environmental effects of aquaculture (as currently practiced), it is increasingly problematic to increase the farming of fish. Since wild fish stocks are under pressure and fisheries are dwindling (FAO 2018a), a critical situation will arise for our access to nutritional super-unsaturated fatty acids like omega-3 fatty acids. One possible solution to the problem of farming more fish is via so-called integrated multi-trophic aquaculture (IMTA). IMTA involves selected seaweeds (mostly kelps for a part of the season) in an ecosystem with fish and filter feeders such as shellfish (Chopin 2013; Correia et al. 2020), i.e. the uneaten feed and dissolved wastes of one trophic level (generally carnivorous fish) are regained and used as feed, fertilizers and energy for multiple species in lower trophic orders. Specifically, the seaweeds exploit the excess nitrogen and inorganic waste from the fish (at least for the parts of the year they are present) and molluscs can take advantage of the organic debris and uneaten fish feed.

Seaweeds and the plastics crisis

Modern societies without plastics are almost unimaginable and in particular after WW2, plastic products have been an omnipresent commodity in peoples' material life. From being considered a reusable resource, more than 90% of plastics are now single-use plastic that are designed to be used only once, in particular for packaging, and only a few percent of this plastic is being recycled. More than 10% of the solid waste from households are now plastics. As a consequence, 8.3 billion tonnes of massive plastic pollution have been piled up on the planet over the last 60 years (Geyer et al. 2017) and the mass is rapidly increasing. The poorly degradable plastic waste ends up in rivers, oceans and landfills where it will stay for hundreds of years. Microplastics are now considered as

having a toxic effect on animals and the environment. We are facing a veritable plastic crisis that is endangering our environment and the ecology of the planet to an extent that plastics have been proposed as a geological indicator of the Anthropocene (Zalasiewicz et al. 2016).

Circular economy, regeneration and reuse of plastics is one way to mitigate the disaster. Development and use of bioplastics from non-petroleum biomaterials constitute another route involving biodegradable, inexpensive, and natural resources, and it is here that seaweeds may come in as part of the rescue plan (Rajendran et al. 2012; Phipps 2020). Bioplastics are typically produced using corn, vegetable oil and starch, but since these products are also human food, farming them for plastics will use valuable land, require fertilizers, fresh water and possibly contribute to a future food crisis. Using farmed seaweeds for bioplastics could mitigate some these problems.

Most bioplastics that are produced on a commercial scale are poly-lactic acid poly-hydroxyalkanoates, starch plastics, cellulose plastics and proteins plastics (Mekonnen et al. 2013) that are biodegradable. Bioplastics from seaweeds are based in particular on the polysaccharides agar, carrageenan and alginate, and seaweed waste from agar extraction has been proposed as a material filler (Zhanga et al. 2019) (Fig. 10). Often, the polysaccharides enter a bio-composite structure with other biodegradable polymers and the introduction of seaweed material has led to plastics that show improved mechanical and thermal performance, e.g. they are more resistant to microwave radiation and less brittle and durable (Rajendran et al. 2012; Madera-Santana et al. 2015), e.g. for use in the pharmaceutical industry (Gade et al. 2013).

A major use of plastics is film for packaging of foodstuff and drinks, and some results have been reported for obtaining seaweed-based infusion sachets and edible containers and films and that are transparent, stretchable and sealable and have basic properties as a film for food packaging (Siah et al. 2015; Khalil et al. 2017). Interestingly, plastic drinking straw rubbish is one of the largest contributors to plastic waste,



Fig. 10 An edible and biodegradable pouch made of seaweeds as a handy container for fresh water. <https://shorturl.at/bjEJQ>

and a range of different seaweeds have been explored for manufacturing a bio-degradable straw (Ardiansyah et al. 2019).

Although some significant progress has been obtained over the last decade, the field of bioplastics from seaweeds is still in its infancy.

Seaweeds for sustainable energy

Access to sustainable energy sources is absolutely critical for all parts of the world now and for forming and sustaining our future. Fossil fuel for transportation and production of electricity is a limited resource and the combustion of fossil material is an over-arching factor behind climate changes and global pollution. Alternative, sustainable and renewable energy production is in great demand. Therefore, seaweeds have been on the radar of the energy sector, where they may be a means of meeting growing global demand and of decreasing the carbon footprint that is attributable to anthropogenic activities in particular with respect to emission of greenhouse gases (Fig. 11).

With a view to solving some of the major problems confronting the transportation sector by finding a replacement for oil and gasoline, significant research activities have been mounted to use both micro- and macroalgae for the production of bioethanol (Kraan 2016; Jiang et al. 2016; Kaur et al. 2018; Gegg and Wells 2019; Gao et al. 2020). However, even after this research, much of this work is still on an experimental scale and the further investments in research and development are highly dependent on the current market price for fossil fuels. Leading companies in the aviation industry are currently experimenting with how to produce biomass from microalgae for third-generation alternative biofuels to power passenger jet planes, and worldwide, a major research effort is being carried out to develop microalgal-based processes for production of



Fig. 11 Seaweeds for production of biofuels. (CC BY-SA 3.0) (<https://bit.ly/2ANu6mS>)

renewable energy (Jacob-Lopes et al. 2019). It is noteworthy that, unlike many other biofuels from land-based plants or edible seaweeds, those based on microalgae and selected non-food-use seaweeds (i.e. some of the red seaweeds of *Gracilaria* spp. or *Eucheuma* spp.) have relatively low-value colloids (i.e., non-agar and carrageenan respectively) and might be an economically viable biomass for mass cultivation as a feedstock for energy) would not displace food crops nor provide competition for freshwater resources.

At present, farming seaweeds for energy production remains non-economically viable, and it would possibly need to be coupled to prior use of the same seaweeds (as waste) that first are used for other purposes, in a MUZE (multiple-use zero effluent) or biorefinery approach such as pollution abatement (Michalak 2020b). In addition to access to sufficient biomass (many millions of metric tonnes in continuous production) of many types of seaweeds for industrial, large-scale biofuel production, there are major scientific and technological challenges involved with design and development of enzyme systems that effectively can break down seaweed polysaccharides into fermentable sugars (Maneein et al. 2018; Ramachandra and Hebbale 2020).

Seaweeds for sustainable eating

It may seem strange that although there are many thousands of different seaweed species in their total diversity, as with land plants, the selection of seaweeds which are commonly eaten is perhaps less than 200 in total, i.e. conservatively less than 2%. This may change as the focus is shifting towards a more sustainable eating behaviour (Mouritsen and Schmidt 2020).

In the report *Food in the Anthropocene*, the EAT-Lancet Commission 2019 on Healthy Diets from Sustainable Food Systems presented a solution for a daily diet that can meet the requirements for feeding a global population of 10 billion in 2050 with a healthy and nutritious diet from sustainable food systems (Willett et al. 2019). The diet implies that humans must each eat 500 g of greens daily, consisting mainly of vegetables, fruit, whole grain, legumes, nuts and unsaturated fats, but only moderate or small amounts of fish and poultry with no, or very little, red meat, processed meat, added sugars, refined cereals and starchy vegetables. Note that likely out of ignorance, marine-produced vegetation, seaweeds and microalgae were missing from this listing of largely terrestrial-based, farmed species. With this recommendation, the Commission argued that it should be possible to meet the United Nations Sustainable Development Goals (United Nations 2019). The Commission pointed out that their solution was indeed fragile, and even a small increase in the consumption of red meat, or dairy products, may catastrophically tip the balance required.

The report is based on a grim background noting that the global food systems in the Anthropocene are the main reason for the changing ecosystems of the Earth, including changes in climate. Agriculture occupies 40% of the land (Foley et al. 2005) and is responsible for 30% of all GHG emissions (Vermeulen et al. 2012), and 70% of the freshwater usage (Steffen et al. 2015). Fisheries have fully exploited 60% of wild stocks, while over-fishing another 30%; as a result, the global catch has diminished in recent decades. The aquaculture of fish and shellfish cannot easily be expanded due to pollution and lack of sustainability in most fish farms. The true cost of this type of food production system has been a significant loss in biodiversity and serious damage to whole ecosystems, as well as the emission of excess nutrients and GHGs. The global cycles of carbon, phosphorus and nitrogen have been disturbed, and food waste from production to consumption is skyrocketing. It is clear that the current global food systems are neither sustainable, nor healthy (Searchinger et al. 2019; Willett et al. 2019) (Fig. 12).

Hence, there is no way around that we have to eat more greenly produced greens (GPGs), i.e. predominantly plant-based foodstuff. Eating more GPGs, e.g. vegetables, is however in itself not a straightforward undertaking. There are two fundamental reasons why a green diet may not be to our liking. One has to do with the biology of the plants and the other is deeply rooted in human evolution (Schmidt and Mouritsen 2020). Green plants are, by nature, generally bitter and lack the sweet and umami tastes that humans, over evolutionary time scales, have become primed to crave (Mouritsen and Styrbæk 2014).

Seaweeds may again come in here as a rescue agent, and although of different colours (i.e. red, brown and green), they may well qualify as GPGs. The EAT Lancet Commission report (Searchinger et al. 2019; Willett et al. 2019) neglected to mention seaweeds as being part of the solution to eating greener although a recent High Level Panel for a Sustainable Ocean Economy highlighted that seaweeds were the fastest



Fig. 12 Seaweed salad composed of mixed species. Courtesy of Jonas Drotner Mouritsen

growing aquaculture (phyconomic) sector with an un-tapped potential for food production (Costello et al. 2019). We would propose that multiple seaweeds have to be considered as part of green, sustainable eating in the future and point out that seaweeds are probably some of the most carbon-neutral types of foodstuff.

There is a considerable literature base about edible seaweeds (Mouritsen 2013; Pereira 2016; Pérez-Lloréns et al. 2018; Ferrara 2020). Global production is around 30 million tonnes of which 97% derives from aquaculture (Buschmann et al. 2017; FAO 2018b). About half of the production is used as human food. Seaweeds are high in both macro- and micronutrients, minerals and vitamins, as well as super-unsaturated omega-3 fatty acids, in particular EPA (Mouritsen 2013; Shannon and Abu-Ghannam 2019). In relation to economic sustainability, a recent calculation showed that the economic value of marine vegetation is almost 20 times higher than that of terrestrial forests per hectare (Pérez-Lloréns et al. 2018). Although globally there is a large production of seaweeds for food, it has been calculated that just replacing 1% of the global human diet with seaweed would require 73 times the current production (Forster and Radulovich 2015). Currently, there are severe phyconomic, economic, technological and regulatory challenges that must be addressed in order to make such an expansion in seaweed production possible (Buschmann et al. 2017).

However, we would like to emphasize that small amounts of selected seaweeds can add to the flavour and texture profile of plant-based foods making them more delectable (Mouritsen and Schmidt 2020). In particular, some seaweeds contribute a substantial umami taste (Mouritsen 2017; Mouritsen et al. 2019a), e.g. in the form of an aqueous extract, dashi, most prominently known from the properties of Japanese konbu (*Saccharina japonica*). Whereas most other brown seaweeds do not contribute much umami (Mouritsen et al. 2019a), the red seaweed dulse (*P. palmata*) is an excellent source of free glutamate and hence the umami taste (Mouritsen et al. 2013). ‘Umamification’ of vegetables may be one route to eating more greens, either by using dashi or seaweeds as whole foods and as a condiment to green dishes. Seaweeds and seaweed gastronomy, recently coined as phycogastronomy (Pérez-Lloréns et al. 2018; Mouritsen et al. 2018, 2019b), should be counted on to provide for more sustainable eating based on the phyconomic principles and prospects of sustainable seaweed aquaculture (Hurtado et al. 2019; Barbier et al. 2020).

Closing remarks

Considering the diversity and global proliferation of the ancient and heterogeneous group of seaweeds covering three different phyla, it may not be surprising that these remarkable organisms with their many spectacular properties have been

linked to the evolution and livelihood of humankind during hundreds of thousands of years. Still, most people are oblivious of their services to us, both during evolution and not least in historical times as well as present days. In this review, we have brought seaweeds into the limelight with a focus on how they have come to rescue during times of crisis, time and time again, and may well come to play an important role at the various crises we are facing today and in the future (Doumeizel and Aass 2020).

Seaweeds may be a game changer in future food, feed, fuel, carbon capture and storage, medicine, disease prevention and health, to name a few areas. Scientific research, industrial innovation, and new operations can, together with governments and multilateral organisations, open the path for new industries to deliver on the 17 UN Sustainable Development Goals, also including ecosystem support, poverty alleviation, ocean restoration and coastal community resilience (United Nations 2019). The time is ripe to learn from history and unlock new seaweed value chains as drivers of the Sustainable Development Goals by investing in scientific research and reap the benefits of the results by exploring novel applications, developing new technologies and globally distributing the positive goods and services to be derived from seaweeds for all humankind.

Funding The work by OGM is supported by the Nordea Foundation via a centre grant to the research and communication centre Taste for Life.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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