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Seaweed global demand:

Component of interest and short- and medium-term trends

Carried out by the GRADEA team composed of:

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Summary

This study is part of a broader study of the global seaweed sector sponsored by the World Bank group. It is part of the World Bank's "Seaweed aquaculture for food security, income generation and environmental health in Tropical Developing Countries" programme to achieve this goal of developing the seaweed industry. This file was carried out by 10 engineering students of ISTOM as part of the educational exercise of the 4th year Young Experts Mission. The objectives of this study were to determine the components of interest in macro-algae (seaweeds), as well as possible changes in market demand in the short and medium term. To meet these objectives the team has carried out a bibliographical research as well as interviews. The bibliography provided all the necessary information one the elements of interest in seaweed, as well as the most recent elements of changes in the demand for algae in certain industries. It also collected information on the new applications as well as the new markets. The interviews provided trends in the various current and future demands, as well as on development issues. All the data collected during the research and interviews were then cross-referenced and compared between each other in order to arrive at a comprehensive analysis of the evolution of the demand for algae in certain sectors.

Acknowledgements

We would like to thank our sponsor, the World Bank, for trusting us and allowing us to work on the development of this project in the field of macroalgae, a vast but enriching subject.

Our thanks go in particular to Randall Brummett, for his accompaniment which facilitated the contact with various actors and Steffen Hansen of the Global Environmental Facility for reading and commenting on drafts.

We would also like to thank all the specialists we interviewed for their time and their sharing of knowledge, which was very precious to us.

Finally, we would like to thank ISTOM, and in particular our tutors Mr. Costera and Mr. Andres for their help in accomplishing our mission.

The GRADEA Team

The following study was carried out by the GRADEA Junior Expert Assignment (JEA). This team consists of ten engineering students in agro-development from ISTOM (Angers, France). This school trains its students in the creation and implementation of economic, social and solidarity activities in the agricultural sector of developing or emerging countries. The teaching tackles development problems, crossing scientific disciplines from the first year of the course: life sciences, basic sciences but also humanities (economics, sociology, ...). Professional skills are gradually acquired through a course that balances theoretical and applied teachings, practical work, field trips, international internships, and the Junior Expert Assignment.

This mission for the World Bank is part of the educational framework set up by ISTOM through its agro-development engineering course. Indeed, at the end of their 4th year, ISTOM students have to implement a specific study for a sponsor working in international development. Different kinds of studies can be implemented: project evaluation, impact study, feasibility study for a product or a process, diagnosis, etc.

Therefore, various subjects or fields can be studied under the following conditions:

- Writing a report with the study results,
- The produced data or synthetis are original,
- Signature of a “training period-type agreement” for the field part of the study between the sponsor, ISTOM and the students.

It is in groups of 8 to 10 that students have to implement their study, in order to propose high level of labor and expertise capacity. They are supervised by a permanent ISTOM teacher throughout the whole preparation process of their study.

This work is part of a long-term project for students, with the expertise being prepared for 16 months before it is completed, between the beginning of the 3rd year and the end of the 4th year. This preparation allows them to establish a draft, to find funding if necessary, to organize their field study but also to write a methodology memorandum adapted to the sponsor’s requests and to the local context.

In addition to the goals of the study, each step of the study is evaluated by ISTOM: draft project, approval by an agreement committee, final restitution before a specific jury etc. GRADEA team has therefore been trained for the implementation of this exercise since October 2018. Members have gathered around the common desire to promote sustainable, responsible, and ethical agriculture around the world. Throughout 2019, the team devoted itself on seeking a sponsor and funding for a potential mission abroad. Meanwhile the team also carried out another exercise imposed by the school, the realization of a Business Plan for the company Plante Innovation SAS, between October 2019 and January 2020. Finally, it is within this sanitary crisis imposed by the COVID-19 that the GRADEA team has committed itself to carry out the following study for the World Bank Group.

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Glossary

AACC: American Association for Clinical Chemistry

ALA: Apha-Linoleic Acid

Antioxidant: Any substance that can delay or prevent oxidation in the presence of oxygen.

ARA: Arachidonic acid

Bioavailability: Fraction of an ingested nutrient utilised for functional demands in target tissue(s).

Biofouling or biological fouling: The undesirable accumulation of micro-organisms, plants, algae, and animals on submerged structures

CODEX Alimentarius (CA): Meaning, literally, "food code", a compilation of standards, codes of practice and recommendations put out by the Codex Alimentarius commission, which meets every 2 years. Membership is open to all countries associated with the Food and Agriculture Organization of the United Nations and with the World Health Organization. The CA has 168 members and covers more than 98% of the world population.

DHA: DocosaHexaenoic Acid

EABA: European Algae Biomass Association

EFAC: European Food Additives Classification

EPA: EicosaPentaenoic Acid

FA: Fatty Acid

FDA: The Food and Drug Administration of the United States.

FUFOSE: The European Commission Concerted Action on Functional Food Science in Europe.

Functional food: A food can be regarded as functional if it is satisfactorily demonstrated to affect one or more target functions in the body beyond adequate nutritional effects, in a way that is relevant either to an improved state of health and well-being and/or the reduction of risk of disease.

GHG: GreenHouse Gas

GRAS: "Generally Recognised As Safe" status

High-density lipoproteins (HDL): Plasma lipoproteins containing low concentrations of cholesterol and other lipids; believed to be beneficial.

HPV: Human PapillomaVirus

IPM: Integrated Pest Management

LA: Linoleic Acid

Lipoproteins: Particles composed of specialised protein and lipids, including triacylglycerol, cholesterol and phospholipid. They enable (water insoluble) lipids to be carried in blood plasma.

Low-density lipoproteins (LDL): Plasma lipoproteins containing high concentrations of lipids (low density compared with that of water), including cholesterol. Increased concentrations are a risk factor for coronary heart disease.

MCA : Multiple Correspondence Analysis

Micronutrients: Vitamins and mineral salts (as distinct from macronutrients – fats, carbohydrates and proteins).

Optimal nutrition: The principle of maximising the quality of the daily diet in terms of nutrient intakes to favour the maintenance of health.

PBS: Plant Bio-Stimulant

PGR: Plant Growth Regulator

Prebiotic: a selectively fermented ingredient that allows specific changes, both in the composition and/or activity of the gastrointestinal microflora that confers benefits upon the host wellbeing and health

Probiotic: A live microbial food ingredient that, when ingested in sufficient quantities, exerts health benefits on the consumer.

PUFAs: Polyunsaturated Fatty Acids

SE: Seaweed Extracts

USDA: U.S. Department of Agriculture

WBG: World Bank Group

Introduction

The following study was conducted by GRADEA, a student association composed of 10 students, in partnership with The World Bank Group (WBG) and ISTOM – Ecole Supérieure d'Agro-Développement International.

With a growing global population, hunger, poverty and climate change become key issues for international institutions such as the World Bank and the United Nation. New employment and feeding their population are major preoccupations of WBG client governments. In this current context, with ocean's covering 71 percent of the Earth's surface, these institutions are turning to seaweed exploitation to answer these challenges. In 2019 the global seaweeds market was calculated to be at USD 5.9 billion and is anticipated to witness a CAGR of 9.1% between 2020 and 2027 (Grand View Research, 2020). Industrial seaweed production is almost entirely sourced from family farms in tropical coastal waters where a scaled-up seaweed industry could have major positive impacts on employment and revenues. Consultation with governments and private sector have revealed a willingness to invest in a larger and more robust industry but question the ability of existing markets to absorb expanded volume in the short and medium terms (World Bank, 2016).

Currently, markets known to the WBG are growing at a rate deemed too low to meet SDG 14. For this novel industry to be scaled, new markets and the opportunity of growth they offer need to be identified. With a multitude of species with each a large variety of compounds, they find applications in many industry sectors such as pharmaceutics, cosmetics, food, feed, nutrition, biotechnology, energy and more.

Stemming from these objectives and questions, in this study, the team of students identified macro-algaes species, components and uses through literature review and conducted interviews of the seaweed sector's actors, that is, industrialists, academics, seagrowers and harvesters. The objective was to identify components of interest and to highlight the industry's demand in seaweed and seaweed extract, existing and emerging markets, and development challenges.

This study had essentially focused on the macro-algae (seaweed with vegetative system clearly visible) applications, and not on the micro-algae (microphyte).

Because it is part of a school exercise, time was a limiting factor, and the students believe this study should be continued. The current document should represent an outline for future studies. Furthermore, because of the nature of the interviews, the information may not fully represent the on-field reality. Information from this study should be taken with the required precautions.

I. Industrial application of seaweeds

Introduction

Algae are living organisms found in aquatic environments. They constitute a very important part of biodiversity and form the basis of freshwater, brackish and marine food chains. Seaweeds are of many different shapes, sizes, composition, and colors, and occupy various habitats. They can be classified into three broad groups based on pigmentation: red seaweed (*Rhodopyceae*), brown seaweed (*Phaeophyceae*) and green seaweed (*Chlorophyta*). To distinguish them from micro-algae (*Cyanophyceae*), seaweed is also known as macro-algae (McHugh, 2003).

Algae have often been considered invasive because of their excessive biomass on the coast which can have adverse effects on the environment. However, they have been used since antiquity for food and agriculture. It is only since the mid-20th century that research has focused on the wide range of properties provided by algae. Industrialists are also beginning to see the promising potential of algae and to use it whole or extracting certain components of interest (Illera-Vives *et al.*, 2020).

Their varied biochemical composition means that they represent a potential source of bioactive compounds for applications in different industries of interest such as agri-food, cosmetics, pharmacology, agriculture and, more recently, in the field of functional food and chemistry. Low in calories, they are packed with essential nutrients of interest, far more than most terrestrial plants.

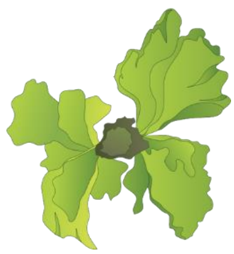
A. Classification of seaweeds

Chondrus crispus

Red seaweed can occur from low tide to 100 meters depth. They are not always red; they can be purple or dark greenish red due to the dominance of R-phycoerythrin pigment. Their cell wall consists of a small amount of cellulose and gelatinous or amorphous sulphated galactans such as agar, carrageenan, furcellarin and others. Best known *Rhodophyceae* include *Pyropia* spp. and *Porphyra* spp., dulse (*Palmaria palmata)*, Irish moss (*Chondrus crispus*), *Gracilaria* spp.*, Euchema* spp. and *Gelidium* spp.

Brown seaweeds live primarily in shallow waters or on shoreline rocks. They are the largest seaweeds; their size can range from 60 centimeter up to 35-45 meters in length. The largest brown algae are also known as kelp, which includes different species. Their color is generally brown to reddish brown due to xanthophyll pigments. The cell wall of *Phaeophyceae* consists of cellulose and alginic acid and they synthesize laminarin and mannitol through photosynthesis. Most common brown seaweeds include *Laminaria/Saccharina* spp.*,* the giant kelp (*Macrocystis pyrifera), Ascophyllum nodosum* or *Sargassum* spp.

Sargassum spp.



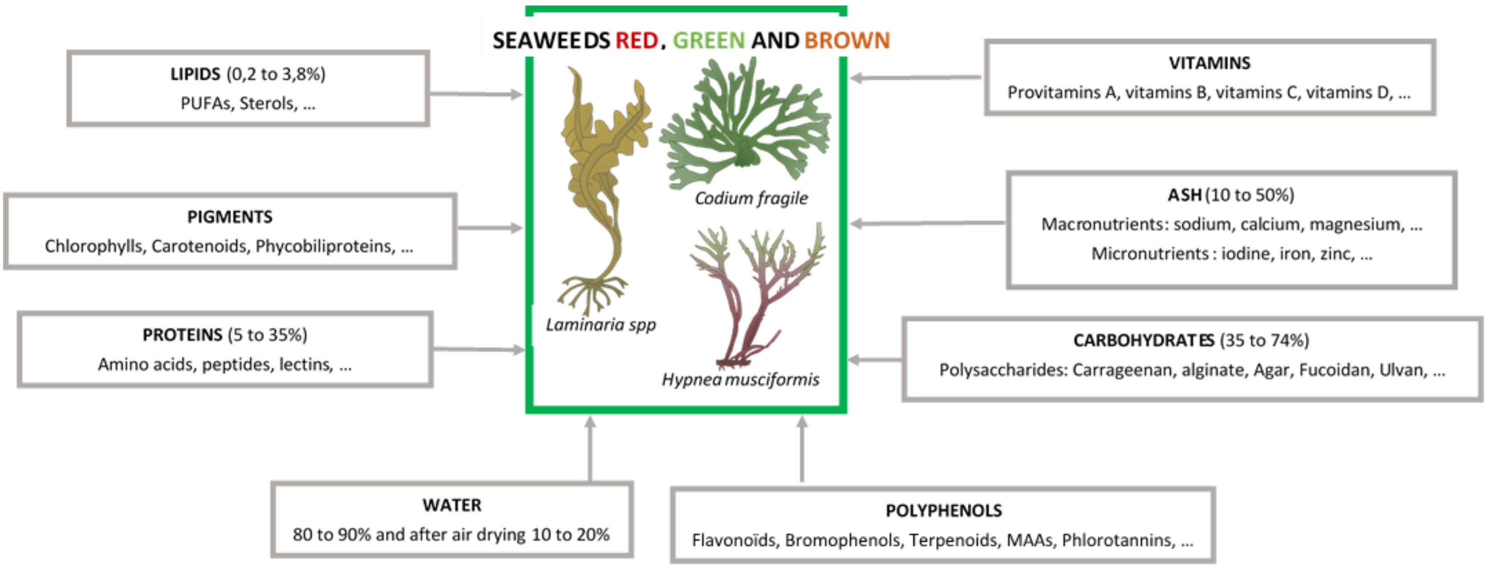
Ulva spp.

Green seaweeds are common inhabitants of marine, freshwater, and terrestrial environments. The abundance of chlorophyll pigments gives them their green to yellowish green color. *Chlorophyceae* cell wall consists of a pectic outer layer and inner cellulose layer which can sometimes be calcified. They produce starch from photosynthesis. Main *Chlorophyceae* genera include *Ulva* spp., *Enteromorpha* spp., or *Caulerpa* spp.

B. General composition of seaweeds – Definition of components

Whether red, green, or brown, macroalgae are full of a multitude of compounds of different interests in varying proportions depending on the species. In general, seaweeds are rich in carbohydrates (35 to 74%) like polysaccharides, several minerals (ash contents vary widely from 8 to 40%, dry weight such as iodine, lipids (0,2 to 3,8%) like polyunsaturated fatty acids (PUFAs), proteins (5 to 35%), essential amino acids, pigments, polyphenols, vitamins and other nutrients. The percentages of the components presented are global averages based on the work of Ito and Hori (1989), Kim (2011) and Peng *et al.* (2015). Numerous studies show that the more or less high presence of constituents varies according to many factors such as species, physiological stage of the seaweed harvest, climatic conditions, water temperature, nutrient concentration in water, etc. (Peng *et al.*, 2015). The constituents of interest are presented in the following Figure 1. All chemical composition values of the seaweed in this document are approximations taken from literature reviews.

Figure 1: General composition of red, green, and brown seaweed



Source: Based on Ito and Hori, 1989; Kim, 2011; Peng *et al.*, 2015

Carbohydrates and dietary fiber

"Dietary fiber (DF) is the edible parts of plants or analogous carbohydrates that are resistant to digestion and absorption in the human small intestine with complete or partial fermentation in the large intestine. Dietary fiber includes polysaccharides, oligosaccharides, lignin, and associated plant substances." (AACC, 2001). DF can be divided into soluble and insoluble fractions. The viscosity of soluble fiber allows a slower digestion and absorption of nutrients, as well as a decrease in blood cholesterol and glucose levels. Insoluble DF increases fecal bulk and decreases intestinal transit time (Abu-Ghannam and Cox, 2013). The average total dietary fiber content in seaweed can vary from 36% to 60% of its dry matter. (Rajapakse and Kim, 2011). Seaweed contains a large amount of carbohydrate as structural, storage and functional polysaccharides, and the total carbohydrate content may range from 20% to 76% of dry weight depending on the species. (Holdt and Kraan, 2011).

Polysaccharides are composed of polymers of sugar units; they are the main structural components of seaweed cell walls (Pangestuti and Kim, 2015). Phycocolloids are seaweed-derived polysaccharides that are used as gelling agents in many ways solely because of their colloidal properties. The most important ones are carrageenans, agar and alginates that are produced in industrial quantities (Armisén and Gaiatas, 2009). However, beyond industrial colloids, it has been demonstrated that seaweed polysaccharides can provide specific health benefits. These include carrageenan, agar, alginate, fucoidan, mannitol, laminarin and ulvan. Their bioactive property allow them to fit into many different industries (Kraan, 2012).

- **Carrageenan** represent between 30% and 80% of the cell wall constituents of certain red seaweeds where it acts as a structuring agent (Venkatesan, Anil and Kim, 2017). In the 1960s, the seaweed *Chondrus crispus* was the most important source of carrageenan, and it is currently found around the coasts of the North Atlantic. This specie has been replaced by *Kappaphycus alvarezii* and *Eucheuma denticulatum*. These seaweeds are extensively spread on the coasts of the Philippines, Indonesia, and other islands in the Far East (McHugh, 2003). Other genera such as *Furcellaria*, *Gigartina* or *Iridaea* are also used as a source of carrageenan. There are several carrageenans, differing in their chemical structure and properties, and therefore in their uses. The carrageenans of commercial interest are called iota, kappa and lambda. For the food industry, carrageenan is classified as E407 in the European Food Additives Classification (EFAC) (FAO, 2018). The main seaweeds commercialized for carrageenan are presented in *Appendix 1.*

- **Agar** is a mixture of polysaccharides composed of agarose, the gelling component, and agropectin which has a low gelling capacity (Armisén and Gaiatas, 2009). It is the major cell wall constituent of certain red seaweed especially from *Gelidium* spp. *Gelidiella* spp. and *Gracilaria* spp. (Kaliaperumal, 2003). These red seaweeds are either cultivated in aquaculture or harvested from natural stocks. Most of agar's commercial production comes from cultivated seaweed (FAO, 2018). Agar is defined as a strong gelling hydrocolloid from marine algae, it is a food additive considered in the USA as GRAS by the FDA. In Europe it is classified as an E406 additive (Armisén and Gaiatas, 2009). The main seaweeds commercialized for agar are presented in *Appendix 2*

- **Alginate** is a structural component of brown algae and a capsular polysaccharide in soil bacteria, so it is quite abundant in nature (Draget, 2009). Most of the brown algae used have a complex breeding cycle that makes their cultivation less profitable than when harvested from wild stocks. The most commonly used species for the extraction of alginates are the *Ascophyllum, Durvillaea, Ecklonia, Laminaria, Lessonia, Macrocystis* and *Sargassum* (McHugh, 2003). The forms of alginate used in the food industry are alginic acid, sodium alginate, potassium alginate, ammonium alginate, calcium alginate and propylene glycol alginate and respectively carry the European additive codes E400 to E405 (Featherstone, 2015). The main seaweeds commercialized for alginate are presented in *Appendix 3.*

- **Fucoidane** is a sulphate polysaccharide contained in the cell walls of brown algae. It is also known as fucan, fucosan or sulfated fucan. Mainly composed of fucose, its chemical structure may vary depending on the source and specie of brown algae from which it is extracted (Lim and Wan Aida, 2017). Fucoidane accounts for 3 to 30% of the dry weight of the seaweed (Person, 2011). It is found mainly in *Sargassum* spp., *Laminaria/Saccharina* spp., *Fucus* spp. (Lim and Wan Aida, 2017). Fucoidanes can be a potential co-product of alginate extraction.

- **Laminarine** exists in the plastides of brown algae where it serves as a storage polysaccharide. Laminarine content can vary from 0 to 35% of dry matter in different species of brown algae (Kadam, Tiwari and O'Donnell, 2015; Olatunji, 2020). Laminarine concentrate on *Laminaria/Saccharina* spp. fronds, but also in smaller quantities in the species *Ascophyllum* spp., *Fucus* spp. and *Undaria* spp (Kraan, 2012).

- **Mannitol** is a polyol found in the cell matrix of several species of brown algae such as *Fucus vesiculosis, Laminaria hyperborea* or *Ecklonia radiata.* It accounts for 10% to 25% of the dry matter of algae (Kaliaperumal, 2003; Kraan, 2012).

- **Ulvane** is a sulphate polysaccharide found in the cell walls of green algae including the species *Ulva amoricana*, *Ulva rigida* and *Ulva enteromorpha* (Alves, Sousa and Reis, 2013). Polysaccharides in the cell walls of ulvales account for 38% to 54% of the dry matter of algae. Two main types have been identified: water-soluble ulvanes and insoluble cellulosic substances (Kraan, 2012).

- The **furcellaran,** also known as "Danish agar", is obtained from the red algae Furcellaria *fastigiate.* The structure of the furcellaran is similar to that of the k-carrageenan. Initially, it was proposed that furcellaran be classified separately from carrageenans under EEC food legislation. However, a reassessment recognized the structural and functional similarity of the two materials and classified them together under the designation E407 (Imeson, 2009).

Polyphenols

Polyphenols are an extremely heterogeneous group of molecules characterized by the presence of one or more benzene rings and the number of hydroxyl groups (Freile-Pelegrin and Daniel, 2014). Industry interest in polyphenols from algal biomass is very recent, so published reports on their exact proportions are unavailable. That is why we do not yet know their exact proportion. Key polyphenols of economic interest in many industries include:

- **Flavonoids** are the largest category of polyphenols. Brown algae generally contain more flavonoids than red or green algae. The highest proportions of flavonoid were found in brown algae *Undaria pinnatifida* (Wakame) with 20-35 mg/g. and *Saccharina latissima* with 2 to 11 mg/g MS (WALSEA, 2020)

- **Bromophenols** are present in the three major groups of algae. In red algae, they have been detected in large quantities in *Ceramiales, Gelidiales* and *Corallinales,* but are also present in brown and green algae (Freile-Pelegrin and Daniel, 2014).

- **The Tepenoids** form a broad and diverse class. They are present in brown and red algae. Meroditerpenoids are found almost exclusively in brown algae of the type *Sargassaceae* and *Sargassum Fallax* (Saraswati *et al.*, 2019). The presence of diterpene-benzoate macrolides has been reported in the red algae *Callophycus serratus* (Bedoux *et al.*, 2014). Red algae also produce halogenated terpenoids as in *Plocanium costatum.* The *rhodophyceae* red algae class is characterized by a large structural diversity of secondary metabolite halogenites (WALSEA, 2020).

- **Mycosporin-type Amino Acids** (MAAS). These are a group of small water-soluble compounds. They are present in large quantities in red algae but also in green algae. (Bedoux et al. 2014) MAA Shinorine is present in the red algae *Asparagopsis armata*. Other red algae such as *Gracilaria gracilis* and *Palmaria palmata* (Dulse) are composed of several MAAs such as Shinorine (WALSEA, 2020).

- **Phlorotannins** are oligomers of phloroglucinol that can precipitate proteins. They are the most studied group of phenolic constituents in algae. They have a unique structure that is not found in terrestrial plants. Phlorotanins account for an average of 25% of dry weight in brown algae (Bedoux *et al.*, 2014). They are found as integral structural components of the cell walls of brown algae such as *Saccharina latissima* and *Undaria pinnatifida* (Wakame). They can also be found in the red algae *Palmaria palmata* (WALSEA, 2020).

Pigments

Pigments are insoluble dye chemical compounds that reflect light in the range of visible wavelengths. Pigments are present in every organism in the world. The Food and Drug Administration (FDA) considers pigments as additives, so pigments are subject to strict regulations. They can be categorized according to different types: their origin (natural, synthetic, inorganic), the chemical structure of their chromophore, their structural characteristics and by name as food additives (Delgado-Vargas, Jiménez and Paredes-Lupez, 2000). Among the main pigments of economic interest in many industries are chlorophylls, carotenoids and phycobiliproteins themselves divided into subcategory, a summary table of pigments and their color is available in *Appendix 4.*

- **Chlorophylls** are mainly found in chloroplasts of higher plants and most algae. They play a major role in plant photosynthesis. There are several types of chlorophyll: chlorophyll A is the most abundant and is present in all algae species. Chlorophyll B is only found in red algae. Chlorophyll C is found in brown algae (Dumay and Morançais, 2016).

- **Carotenoids,** also known as tetraterpenoids, regroup molecules from the families of carotenes and xanthophylls. Carotenoids are in chloroplasts in the form of complex mixtures. They constitute the group with the most sub-pigments. They are orange and yellow pigments. On average, they account for 0.1% of the dry weight of seaweed (Lakhdar, 2018).

- **β-carotene** also known as provitamin A is the most common form of carotene. They are mostly of plant origin like carrots, but also algae. This pigment is transformed by the body into Vitamin A. High values of β-carotene with vitamin A activity were found in green algae such as *Ulva lactuca*, red algae such as *Gracilaria changgi* (Kombu) and brown algae such as Laminaria (Pangestuti and Kim, 2011).

- **α-carotene** are also provitamin A but much less widespread than β-carotene. We find α-carotene in the red algae *Chondrus crispus* and *Palmaria palmata* (Delgado-Vargas, Jiménez and Paredes-Lepez, 2000)

- **Xanthophylls** are yellow molecules. They are found in chloroplasts or chromoplasts in plant cells (Dumay and Morançais, 2016). Among them are:
  - **Antheraxanthin** are present in red algae such as *Gracilaria gracilis*.
  - **Fucoxanthins** are extracted mainly from brown algae such as Laminaria *Japonica*, *Saccharina latissima* and *Undaria pinnatifida.*
  - **Lutein** has the number E161b in food additives. It is found mainly in the red algae *Chondrus crispus* and *Palmaria palmata.*
  - **Violaxanthin** has the number E161E. It is not allowed in France. It is found in red algae such as *Palmaria palmata* and *Gelidium corneum.*
  - **The Zeaxanthin** has the number E161h. It is not listed as a food additive for the European Union. It is found in red algae such as *Gracilaria gracilis*

- **Phycobiliproteins** are water-soluble pigments that capture photons and transfer them to chlorophylls during photosynthesis. They are only found in cyanobacteria and red algae.

  - **Allophycocyanin** are a blue-colored pigment found in *Rhodophyta such as Escheria coli* (Ge et al. 2006) .

  - **Phycocyanin** is found in red algae *Chondrus crispus* (WALSEA, 2020).

  - **Phycoerythrin** can make up a major proportion of red algae cell proteins, at levels of 1.2% and 0.5% of dry weight in *Palmaria palmata* and *Gracilaria tikvahiae* and *Gracilis,* respectively (Fortier and Florentin, 2020).

Proteins

Proteins are biological macromolecules found in all living cells. There are thousands of micro or nano-proteins. They are made up of one or more polypeptide chains, series of amino acid residues linked to each other by peptide bonds. Depending on the type of algae, between 5 and 35% protein is found (Ito and Hori, 1989). They are very important for living organisms because of their roles as enzymes or structural components. As a result, proteins are essential in the diet (Linden, 2014). Red algae have the highest protein level, followed by green algae and brown algae. Red algae of the genus *Porphyra* have the highest protein level (47% of total dry weight) slightly higher than the species *Palmaria palmata*

(35% of total dry weight) (Boulho, 2017) and *Gracilaria changii* (34% of total dry weight) (Rajapakse and Kim, 2011)

- **Amino acids** are molecules that are used in the composition of proteins. There are about 100 amino acids but only 22 of them are encoded by the genome of living organisms. Amino acids determine the specific chemical properties of a protein. Amino acids can be divided into three groups: essential amino acids, non-essential amino acids, and conditional amino acids. All amino acids are present in algae at varying proportions depending on the species (Boulho, 2017). *Appendix 5:* **Amino acid profile of red, green, and brown seaweed**presents de amino acid profile of red, green, and brown seaweeds.

- **Lectins** are proteins that connect reversibly to certain carbohydrates. They are involved in certain biological processes, at the level of cell recognition. Eating foods rich in lectins can cause certain disorders such as vomiting. Lectin is found in green algae of the *Ulva* spp type. (WALSEA, 2020).

- **A peptide** is a short chain of 2-50 amino acids linked together by peptide bonds. These amino acid fragments are inactive in the parent protein sequence but can be released during gastrointestinal digestion, food processing or fermentation (Pangestuti and Kim, 2015). Also, studies have recently focused on the identification of peptide groups after hydrolysis of proteins of various macroalgae such as red algae *Solieria chordalis* and *Palmaria palmata*, green algae such as *Ulva lactuca* and brown algae such as *Saccharina longicruris* (Boulho, 2017).

Lipids

Lipids are fat, they are either hydrophobic or amphipathic (a hydrophobic part and part hydrophilic). Energy filled nutrients; lipids are essential to the proper functioning of the body (Hersant, 2015).

Macroalgae are known to be a low-energy, low-calorie food. Indeed, the lipid content of algae is very low with average concentrations between 0.60% and 4.15%. However, this level can rise very high in cultured algae (up to 70% of dry weight in crops specifically bred to produce lipids) (Cotas *et al.* 2020). Among the most interesting lipids are:

- **Sterols** are neutral lipids. They contain a significant supply of energy. They are lipid constituents of cell membranes, which regulate fluidity and membrane permeability. The main sterols of macroalgae are cholesterol, fucosterol and isofucosterol (Elia, 2019). Sterol is a precursor to vitamin D. Interesting amounts of sterols are found in *Gracilaria gracilis* red algae (WALSEA, 2020).

- ***Polyunsaturated fatty acids* (PUFA)** are all fatty acids (FA) containing more than one unsaturated carbon atom (double bonding) in their skeleton. Although the total lipid content is low, marine macroalgae are rich in PUFAs in the n-3 (omega-3) and n-6 (omega-6) series. PUFAs cannot be synthesized by the body, so they must be brought by food. Seaweeds are essentially the only organisms capable of producing long-chain PUFA (Boulho, 2017) ranging from 14 to 24 carbons. PUFAs are found in *Chlorophyta* green algae and *Phaeophyceae* brown algae. Red algae such as *Gigartinales, Corallinales* and *Gracilariales* (Van Ginneken et *al.* 2011) are very rich in EPA, ARA, ALA and LA (Cotas *et al.* 2020)

- **Omega-3** is formed mainly of apha-linoleic acid (ALA), eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA). EPA and DHA are the most predominant compounds with concentrations of up to 50% of total AG content in some algae (Elia, 2019). ALA, an essential fatty acid, is converted into EPA and DHA in our body. EPA and DHA are essential for cardiovascular and nervous system health. Inadequate intake can lead to the development of heart and neurodegenerative diseases. Some studies show that the conversion of ALA to EPA and DHA is low and depends on many factors. It is therefore best to absorb DHA and EPA directly into the diet. These two PUFAs are only present in products from the sea such as oily fish (from their diet based on phytoplankton and algae) and seaweed. Red algae *Palmaria palmata*, contain high proportions of EPA (Van Ginneken *et al.* 2011) .

- **Omega-6** is formed by many acids, the most important are linoleic acid (LA) and arachidonic acid (ARA). LA is an essential fatty acid and is converted into ARA in the body. ARA is essential because it plays an important physiological role. Some studies show that the conversion of LA to ARA is low and depends on many factors. It is therefore better to absorb in the diet directly from ARA (Van Ginneken *et al.* 2011). This PUFA is only found in seafood such as oily fish and seaweed, as well as meat products.

Vitamins

Vitamins are organic substances essential to the proper functioning of our body even if they have no energy value. For most of them, the human body is unable to manufacture them. Their intake through food is therefore essential. Too much vitamin does not improve the performance of an organism that is already functioning normally. Overconsumption can have toxic effects. On the other hand, insufficient intake can lead to deficiencies associated with clinical or pathological disorders (Anses, 2017).

- **Provitamin A** also known as β-carotene is a pigment in the carotenoid family (*Cf.* part Pigments).

- **Vitamin B12:** also called cobalamin are water-soluble vitamins essential to the proper functioning of our body. A deficiency in vitamin B12 causes many disorders in our system. Vitamin B12 is mainly found in foods of animal origin. Most terrestrial plants are unable to synthesize vitamin B12 (Cotas et al. 2020) . This is why, in a strict vegetarian or vegan diet, the intake of vitamin B12 is quite low. As a result, this vitamin can easily become deficient (Kim, 2011). Numerous studies show that nori-type red algae nori such as *Porphyra* and *Pyropia* produce exceptional amounts of bioavailable B12 suitable for vegetarians (Cho and Rhee, 2019)..

- **Vitamin C, D, E, and other B vitamins:** All these vitamins are essential to the proper functioning of our bodies and are found in most commonly consumed foods around the world. Vitamin C (ascorbic acid) is found in many fruits but is also found in brown algae *Laminaria* and *Undaria* (Kim, 2011). Vitamin E is found in cereals, oilseed fruits and vegetable oils, but can be found in Wakame and Dulse (Rajapakse and Kim, 2011). Vitamin D is found in animal products and some vegetable oils. B vitamins (except vitamin B12) is found in fruits, vegetables, cereals, animal foods, vitamins B1 and B are found in Wakame and Kombu. All these vitamins are found in the majority of algae at different proportions (Kim, 2011)

Minerals

Seaweeds are known to be high in mineral content due to their marine habitat. It has been determined that their mineral content is 10 to 100 times higher than traditional vegetables (Holdt and Kraan, 2011). The total ash content of seaweed, including minerals, varies considerably from 8 to 40% of the dry weight (Ito and Hori, 1989). Mineral macronutrients include sodium, calcium, magnesium, potassium, chlorine, sulfur and phosphorus whereas the micronutrients include mainly iodine, iron, zinc, copper, manganese, fluoride or nickel. Seaweed is a primary source of iodine, a micronutrient essential for human health. (Rajapakse and Kim, 2011)

It has been shown that ash content was higher in brown (30 to 39%) than in red seaweeds (20 to 21%) even if many factors impacts the total content such as environment, time, physiology etc. (Rupérez, 2002).

C. Properties of compounds with multi-sectorial interest

Thanks to their multitude of components with varied properties, algae are exploited in many sectors such as food, feed, agriculture, medical, pharmaceutical, cosmetics, nutraceuticals and other sectors like biofuel that will be discussed in this section.

Each sector is in different stages of research and development depending on the algae extracts used. The exploitation of algae is in its infancy, and many studies will have to be carried out before understanding the potential of algae is 100%.

Figure 2 provides an overview of the sectors of interest and the presentation of the properties of the algae that will be exploited there.

Figure 2:

Natural active compounds with a multi-sectorial interest:

***Ulvanes, phycoerythrin, MAAs, phlorotannins, flavonoids, minerals etc*.**

FOOD

- Active proteins
- Thickening and gelling agent
- Additives
- Coloring agents

FEED

- Methane emission reduction (via cattle feed)
- High nutritional value for livestock
- Prebiotic
- Additives

AGRICULTURE

- Alternatives to traditional agricultural chemical inputs: fertilizer and biostimulants
- Antiviral in agricultural uses

MEDICAL

- Anti-diabetic
- Antibiotic substitute molecule
- Cataract and macular degeneration prevention
- Neuroprotectors
- Glioprotector
- Reduction of cardiovascular diseases
- Immunosuppressant
- Antiviral activity
- Oncology: antitumor activity (colon, prostate, etc.)
- Immune defenses stimulation

BIOTECH / CHEMISTRY

- Natural dye
- Synthesis precursors
- Catalyst
- Gel in biotechnology
- Fluorescent markers

PHARMACEUTICAL

- Anti-allergic
- Phlebotonic drugs
- Immunomodulator
- Cholesterol regulation
- Natural anticoagulant
- Antibacterial
- Gastro protector

COSMETICS

- Antioxidant
- UV protection
- Collagen source
- Hyaluronic acid source
- Anti-elastase
- Texturizing agent
- Epidermis - dermis vector

NUTRACEUTICALS

- Mineral enriched food supplements: Iodine, Iron, Zinc, Natural Calcium
- UV protection
- Dietary fibers

OTHER

- Biomaterials, an alternative to plastic
- Textile, dye fixative
- Treatment of wastewater
- Biogas, alcohols, biodiesel
- Pollution bioindicators

Source: Adapted and translated from WALSEA

Food

Seaweed is a very versatile product and widely used in the food industry for direct or indirect consumption. The consumption of seaweed dates back several thousand years especially in Asia where they are part of traditional eating habits and remedies. Today, Asian countries are the biggest consumers of seaweed as a food. However, thanks to migration and cultural exchanges, algae are increasingly found in the Americas and Europe. Despite this broad history, algae remain an underexploited plant resource today. (Tiwari and Troy, 2015). Algae are present in the human diet in several forms: in direct consumption (fresh or dried seaweed), as an ingredient or food additive. This section deals only with the presence of algae in the food industry. The use of algae in dietary supplements for their bioactive properties are presented in the section on In conclusion, this section highlighted the main biological activities that are currently attracting the greatest interest from pharmaceutical companies for drug development, or research in the field of medicine. This allows to highlight components of interest to this sector such as sulphate polysaccharides, fucoidan, laminarin, phycobiliproteins, phenolic compounds or pigments.

Nutraceuticals.

Direct consumption

Most of the seaweed grown is consumed directly as a sea vegetable in Asia in particular. One of the main reasons for this consumption is the high nutritional value of algae. Indeed, edible algae are very rich in bioactive compounds with many beneficial properties for health. Some consider algae to be functional foods[1] (Holdt and Kraan, 2011; Gomez-Zavaglia *et al.* 2017) . This is why algae can be incorporated into eating habits to help meet recommended daily intakes of essential minerals and trace elements (iodine, calcium, etc.), vitamins (B12, E etc.), fatty acid ω-3 as well as other specific components such as fucoxanthin, fucosterol or phlorotannin (Burtin, 2003)..

In addition, their high soluble dietary fiber content, including some polysaccharides, is also of interest to human food. Because they cannot be digested by human, they have no direct nutritional effect on the human body. However, they indirectly contribute to the human diet by increasing the feeling of satiety and facilitating intestinal transit. It has been shown that dietary fiber in algae reduces the risk of colorectal cancer, suppresses gastrointestinal inflammation, and encourages the action of probiotics. Recommended daily intake of dietary fiber is 20 to 30 g per day. On this basis, an 8 g serving of algae can provide up to 12.5% of an adult's daily fiber requirement. Compared to other terrestrial vegetables, the amount of fiber brought by algae is very important (MacArtain *et al.* , 2007; Rajapakse and Kim, 2011).

The biggest direct consumers of algae are China, Japan, and the Republic of Korea. They use seaweed as ingredients in salads, soups or as a sheet to wrap sushi *(Nori).* Seaweed is also consumed in Europe, Latin America and the United States thanks in part to the evolution of the reputation of sushi (FAO, 2018). The main edible algae are presented in ***Erreur ! Source du renvoi introuvable.***.

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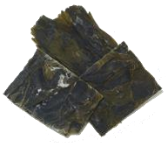
[1]A food is "functional" if: "it is satisfactorily demonstrated to affect beneficially one or more target functions in the body, beyond adequate nutritional effects, in a way that is relevant to either and an improved state of health and well-being and/or reduction in risk of disease" (Ashwell, 2002)

Table 1: Main edible seaweed (sea vegetables) from red, brown, and green macroalgae

	Common name	Species	Application	Region
	Red seaweed			
	Nori	*Porphyra* spp.	Cultivated for food	Asia
	Dulse	*Palmaria palmata*	Culinary ingredient, flavor-enhancer	USA, Canada, Scotland, Ireland, Iceland
	Brown seaweed			
	Wakame	Undaria pinnatifida	Fried in oil, boiled in soup	Japan, Korea, China
	Kombu/Kelp	*Laminaria spp.*	Soup, fried in oil, with soy sauce	Asia
	Sea spaghetti	*Himanthalia elongata*	Used as a vegetable, salad or cooked	Ireland, France
	Green seaweed			
	Aonori	*Monostroma* spp.	Salads, soups, relishes, meat and fish dishes	Europe, Asia
	Sea lettuce	*Ulva lactuca*	Soups, salads	Europe, USA, Asia, Australia, New Zaeland

Source : Based on Gomez-Zavaglia *et al.*, 2017

Food additives: phycocolloids

While the Asian continent is a major consumer of fresh algae, the European and American continents use algae almost exclusively for hydrocolloid extraction. Algae hydrocolloids, or phycocolloids, are mainly used to improve the texture of food products through their gelling, stabilizing, thickening and emulsifying properties. Among them, the most used are carrageenans, agars and alginates. They are widely used in the food industry as a substitute for traditional animal gelatins. (Ali Ahmed et al. 2017 Venkatesan, Anil and Kim, 2017). The ***Erreur ! Source du renvoi introuvable.*** presents the main phycocolloids and their applications in the food industry.

Table 2: Potential applications of carrageenans, agar, and alginate in diverse food products

Product categories	Polysaccharides	Potential application
Baked goods Beverages Confectionery Dairy Desserts Dressings and dips Fried foods Frozen foods Meat analogs Meat products Pasta Restructured products Sauces and gravies Snack foods Soups{Citation}	*Carrageenans*	- Emulsifier - Fat replacer - Water binding agents - Controls syneresis - Improves texture - Creates creamy mouth feel - Enhances fiber content - Antioxidant activity - Antimicrobial activity - Encapsulation of food flavors - Increase yield and hence reduces production costs
	Alginate	- Controls syneresis - Emulsifier - Enhances mouth feel - Improves viscosity - Antioxidant activity - Antimicrobial activity - Anti-browning activity - Moisture retention - Texture improvement - Enhances fiber content - Increase yield and hence reduce production costs
	Agar	- Syneresis control - Emulsifier - Adds texture - Reduces sugar bloom - Enhances fiber content - Increase yield and hence reduces production costs

Source: From Venugopal, 2019

- *Carrageenans & furcellaran*

Carrageenans have the property of forming hot gels (up to 60°C). There are three main forms in the food industry, classified by concentration of sulphate. A comparison of the properties of the different carrageenans is available in *Appendix 6.*

In general, the kappa carrageenans (κ) form a rigid, elastic gel in the presence of potassium. Iotas (ι) form a soft, resistant gel in the presence of calcium and lambda (λ) do not form gel, they are mainly used as thickener (Imeson, 2009). The furcellaran has the same properties and uses as the kappa carrageenans.

Carrageenans play an important role in the dairy industry because of their unique ability to create complexes with milk proteins. These properties have led to the development of many milk-based applications such as desserts, ice creams, creams, yoghurts, cheeses etc. They are also found in processed meat products such as hams and pâtés to increase water retention and thus the volume of the product. In canned goods, carrageenans are mainly used to stabilize and improve the sensation in the mouth and the characteristics of taste release. In the brewing industry, carrageenans are used to clarify beer, wine and honey (McHugh, 2003; Featherstone, 2015).

- *Agar*

Agar has structural and functional properties similar to those of carrageenans. It forms insoluble gels with cold water and is heat-resistant up to 85°C. These properties allow it to play an important role in different industries. Agar is marketed as packets of fine agar, membrane, cut, flakes, granules or powder (Featherstone, 2015). Applications of agar found in several regions and cultures of the world are listed in *Appendix 7.*

Agar is widely consumed in Asia in the form of flavored jelly, whose creamy texture is particularly appreciated. Agar is used in the food industry as a gelling agent and thickener with particularly good properties in acid dairy products where it is used as a stabilizer. It is also found in low-fat products, canned goods, foam-based preparations, etc. (McHugh, 2003). One of the main users of agar is the bakery industry where the very high melting points of agar gels make them particularly suited to the cooking process. Agar has good compatibility with sugar and can be used in very high sugar environments that would precipitate most other gums. It is found in the frostings of doughnuts, sweets and creams etc. (Olatunji, 2020).

- *Alginate*

Alginate has long been used in food and is used as an additive in the food industry for its ability to improve, modify and stabilize food texture. It is found, for example, as a viscosity enhancer, gelling agent, or as stabilising or dispersing agent for watery emulsions (Draget, 2009). It is widely found in the food industry, particularly in reconstituted products, dairy products and canned goods. It allows, for example, control of the melting of ice creams and stabilization of salad dressings. Unlike carrageenan, it does not need heat to gel, so it is used with heat-sensitive foods such as meats, fruits and vegetables (Alba and Kontogiorgos, 2019). The different applications of alginate in food products are described *Appendix 8.*

- *Mannitols*

In the food industry, mannitol is commercially produced to help reduce calories from sugars in packaged foods. Its most common application is in chewing gums, both as a sweetener and as a powder to facilitate packaging. Mannitol is also a useful component in chocolate coating for ice cream and sweets due to its high melting point and color retention at high temperatures. Mannitol can also be used to maintain the proper moisture level in food. (Holdt and Kraan, 2011)

Food additives: pigments

The natural origin of plant pigments allows them to have a place in the food industry because they pose less health risk than synthetic pigments. In addition, their natural origin allows them to be exempt from specific certification to be considered a food additive by the FDA or EFAC (Delgado-Vargas, Jiménez and Paredes-Lupez, 2000)

Red, brown and green algae are excellent sources of a wide range of original pigments with organoleptic properties and health benefits. (Aryee, Agyei and Akanbi, 2018). Their applications as additives presented in this section are specifically related to their roles in food coloring. A summary table of the industrial applications of pigments is available in *Appendix 9*.

The use of pigments in the food industry includes the coloring of fermented dairy products, ice cream, chewing gum, soft and alcoholic drinks, desserts, sweets, or milkshakes. They can also be found on cake decorations thanks to their fluorescent properties (WALSEA, 2020). ***Erreur ! Source du renvoi introuvable.*** shows certain pigments from algae used as a dye in the food industry.

Table 3: Main coloring pigment used in food

Pigment		Color	Seaweed
Phycobiliprotein	C-phycocyanin	Blue	Red
	B-phycoerythrin	Rose	Red
	R-phycoerythrine	Red	Red
Carotenoids	B-carotene	Yellow / Orange	Brown, Green
	Antheraxantin	Yellow	Red, green
	Fucoxantin	Orange /Brown	Brown

Source: Adapted from Fleurence and Levine, 2016

Pharmacology and/or Medicinal Application

As previously presented, algae produce a wide range of bioactive compounds in response to their often-challenging environmental conditions. These compounds have enormous potential in pharmacology and medicine. A growing number of scientific reports highlight the diversity of biological properties of algae and their health potential. (Gomez-Zavaglia et al. 2017) . The purpose of this section is to present the main properties of algae applicable in the pharmaceutical and medical industries.

Antibiotic, antiviral, and antifungal activity

The antibiotic activity of algae has been demonstrated by several authors in tests of algae extracts and Gram-positive and Gram-negative bacteria. The discovery of these new sources of antibiotics is interesting because the resistance of microorganisms to drugs is increasing, so it is essential to provide new drugs today. This is why new natural antimicrobial compounds with high potential, good availability, low toxicity and reduced negative effects are needed (Omar, Al-Judaibi and El-Gendy, 2018).

Macroalgae provide a wide variety of natural bioactive compounds with antimicrobial activity, such as polysaccharides, polyunsaturated fatty acids, phlorotannin and other phenolic compounds, and carotenoids (Pérez, Falqué and Domunez, 2016). The researchers subjected 80 species of algae to bacterial and fungal tests. Of these, 70% had antibacterial activity, but only 27.5% showed antifungal activity (Padmakumar and Ayyakkannu, 1997).

The possible uses of these properties in the pharmaceutical and medical industry are very broad given the importance of these features. For example, antibacterial and antifungal properties allow treatments for acne, gastritis, or ulcerations. Algae antivirus activity can be applied against viruses such as dengue, immunodeficiency viruses (HIV), herpes etc. (Pérez, Falqué and Domunez, 2016)

Antioxidant activity

The risk of diseases due to oxidative stress is compounded by an unhealthy lifestyle, exposure to chemicals, pollution, smoking, drugs, disease, and stress, etc. Antioxidants are substances that can trap free radicals and help reduce the incidence of oxidative stress-induced damage (Sen and Chakraborty, 2011).

Numerous studies have demonstrated the antioxidant activity of certain components extracted from algae on living organisms. These include alkaloids, flavonoids, phenols, tannins, phlorotannin, terpenoids, pigments, glycosides, and steroids. Polysaccharides also play an important role as antioxidants and inhibitors of oxidative damage in living organisms. (Abu-Ghannam and Cox, 2013; Omar, Al-Judaibi and El-Gendy, 2018; Gomez-Zavaglia et al. 2019)

Appendix 10 lists the major groups of antioxidant compounds in macroalgae with specific examples.

The commercial use of algae for their antioxidant properties is still in its infancy. Further research is needed to establish the bioavailability of specific compounds (Cornish and Garbary, 2010)..

Anticancer and antitumor activity

Today, cancer is one of the major diseases that attack modern society on a global scale. Lifestyle, radiation and exposure to various carcinogens/mutagens cause cancer and death in the world's population. This is why research is intensifying to find solutions to this disease. Overall, there are three strategies for treating cancer (Deéléris, Nazih and Bard, 2016):

- Prevention: Promoting behaviors that reduce the risk of developing cancer
- Surgery: removal of the tumor usually before the development of metastases
- Radiation therapy or chemotherapy: induction of tumor cell death in a targeted way

Most research on algae anti-cancer and anti-tumor activities highlights their role in cancer prevention rather than in its treatment.

The first research on algae anti-cancer activity took place in Asia, where algal consumption is very high. It has been observed that Japan's industrialization has resulted in a decrease in direct consumption of seaweed in the population. During the same period, an increase in prostate, colon and breast cancers was reported. Some researchers have since tried to explain the relationship between algal consumption and carcinogenesis. Several reports have suggested that a diet rich in algae would have a preventive effect against the development of cancers. (Oiso, 1975; Delegates, Nazih and Bard, 2016)

Among the promising components, terpenoids and polysaccharides of some brown algae have been shown to hold promise for anti-cancer medicine. The spread of breast cancer can be blocked by unsaturated fatty acids in algae. Or the production of halogenated hydrocarbons such as phenols, terpenes, fatty acids and polysaccharides sulphate by red and brown algae has antitumor activity. (Omar, Al-Judaibi and El-Gendy, 2018). In addition, some studies have linked the anticancer capacity of some algae to the content of compounds with antioxidant properties.

Anticoagulant activity

Phlorotannin and sulphate polysaccharides such as fucoidans in brown algae, carrageenan in red algae and ulvans in green algae have been recognized as potential anticoagulant agents (Wijesekara, Pangestuti and Kim, 2011; Gomez-Zavaglia *et al.*, 2017). Therefore, these components have great potential for development as anticoagulant drugs in the pharmaceutical and medical fields.

However, this anticoagulating activity was mainly studied *in vitro* or on mice. Therefore, and due to the significant value of this property, further studies are needed to find real applications in pharmacology and medicine (Kim and Wijesekara, 2011).

Anti-inflammatory activity

Inflammation is an important response of the body that helps overcome various homeostasis problems such as microbial infections, tissue stress and certain injuries. Excessive and uncontrolled inflammatory conditions can be pathogenic in and of itself, and also affect the pathogenesis of various diseases (Saraswati *et al.*, 2019).

Currently, intensive screening of anti-inflammatory agents from natural ingredients is carried out to determine alternatives to synthetic drugs. Many of the components extracted from algae have anti-inflammatory and immuno-modulatory properties such as PUFAs, phlorotannin, lectin proteins, phycobiliproteins and some saturated polysaccharides. For example, laminarin and fucoidan are used by the health industry and marketed for their activities beneficial to the immune system. (Smit, 2004).

Antilipemic, hypocholesterolaemic and related activities

Cardiovascular disease is mainly associated with high plasma cholesterol and blood pressure. Some polysaccharides and fibers from macroalgae such as alginate, carrageenan, fucoidan, laminarin, porphyrin and ulvan have been found to cause cholesterol and hypolipidemic positive responses due to reduced absorption of cholesterol in the gut (Smit, 2004).

Other activities

As can be seen, the components of algae have potential in the pharmaceutical and medical industry thanks to their wide range of bioactive properties. The main ones have been presented above but there are many others that can be very specific.

For example, fucoidan can play an important role in tissue regeneration (skin, muscle, heart, etc.). (Li *et al.*, 2008). Other studies highlight the contraceptive activity of certain components derived from red algae (Gomez-Zavaglia *et al.*, 2019). Research has evaluated the effectiveness of a carrageenan-based lubricant gel in reducing the risk of human genital papillomavirus (HPV) infections in women (Magnan *et al.*, 2018). Phycocolloids are also used in pharmacology as a suspension agent and stabilizer in certain medicines, lotions, and medicinal creams. Finally, another example is the use of agar in the manufacture of capsules for medical applications and in the form of artificial tissues for research (Holdt and Kraan, 2011).

In conclusion, this section highlighted the main biological activities that are currently attracting the greatest interest from pharmaceutical companies for drug development, or research in the field of medicine. This allows to highlight components of interest to this sector such as sulphate polysaccharides, fucoidan, laminarin, phycobiliproteins, phenolic compounds or pigments.

Nutraceuticals

Dr. Stephen DeFelice coined the term "nutraceutical" from "nutrition" and "pharmaceutical" in 1989. The term is now commonly used but does not have a regulatory definition. This is why it is difficult to distinguish functional foods, nutraceuticals and dietary supplements (Kalra, 2003).

As defined above, functional foods are foods that provide health benefits in addition to basic nutrition. (Ashwell, 2002; Kadam and Prabhasankar, 2010). Nowadays, there is a growing awareness of these functional food ingredients. Hence, one of the main areas of research in Food Science and Technology is the extraction and characterization of new natural ingredients with biological activity (e.g., antioxidant, antiviral, antihypertensive, etc.) (Plaza, Cifuentes and Ibáñez, 2008).

Algae and their compounds with bioactive and nutritional properties are increasingly seen as a potential source of functional ingredients. The most coveted compounds for dietary supplements are dietary fibers, vitamins, fats and minerals (Kim, 2011).

Cosmetics

Recently, the cosmetics industry tends towards the development and production of cosmetics based on natural compounds. As previously presented in Part I.B algae are characterized by their high content of vitamins, essential amino acids, and minerals. Therefore, seaweed extracts are widely used in the cosmetic industry. These macroalgae ingredients can have one of three main functions (Bedoux *et al.*, 2014):

- they are considered as additives which contribute to organoleptic properties;
- they are used for stabilization and preservation of the product;
- they are bioactive compounds which fulfil a real cosmetic function and activity

As in the food industry, polysaccharides are used as stabilizers, thickeners and emulsifiers in sticks, creams, lotions, soaps, shampoos, toothpastes, foams, and gels. Pigments like R-phycoerythrin is used as a natural dye for creams and makeup products (Bedoux *et al.*, 2014).

As for the biological activities of the compounds, algae are mainly found in cosmetic products thanks to their moisturizing, anti-aging, anti-UV, antioxidant, anti-acne, anti-cellulite, collagen booster or skin lightening properties (Olatunji, 2020). Recent research has developed antioxidant skin creams using a mixture of agar and melanin (Roy and Rhim, 2019).

Animal health and feed

The use of algae in animal rations has always been a controversial topic. In coastal areas, some herders regularly gave algae to their animals without understanding why algae were beneficial to their herds (Linden, 2014). It is in 1917, since the first edition of Feeds and Feeding: *The Essential Elements of Feeding, Care and Management of the Animal Farm, including Poultry,* (Evans and Critchley, 2014) that we now know the nutrients necessary for the proper growth, reproduction and development of farmed animals . Thanks to these advances, the aim has been to formulate animal rations at a lower cost and to balance them through different components. It was at the beginning of the 20th century that the commercial harvesting of seaweed for use in animal rations began (Evans and Critchley, 2014). Through their unique bioactive compounds, macroalgae begins to intervene as a dietary supplement in animal nutrition to directly increase the health and well-being of the animal or the quality of the finished product (CEVA, 2011)

Feed

As mentioned above, the nutritional value of algae lies in the combined presence of minerals, fiber, protein, vitamins, and lipids. The nutritional needs of animals and humans are quite similar. In the animal feed industry, seaweed meal is increasingly being used as a dietary supplement. Seaweed is added to the diet in various forms: complete, as a bioprocess residue or as an ingredient for its bioactive component (Linden, 2014). Algae is chosen based on its high proportion of proteins, minerals, or other components of interest. In order to optimize the nutrition of the animals, it is possible to mix the algae according to their proportion in components of interest. As for extracts of compounds of interest to animal nutrition (feed additives), they are still quite expensive.

- *Ascophyllum nodosum*

Nowadays the most used seaweed for animals in food applications is the brown algae *Ascophyllum nodosum*. It has been used in animal feed for decades (Evans and Critchley, 2014) due to its abundant presence in the northern Atlantic Ocean and on the northwest coasts of Europe to the northeastern coasts of northern America (Makkar *et al.*, 2016). *A. nodosum* has many animal nutritional advantages thanks to the presence of proteins (between 3 and 15% of dry weight) that have different structures than those found in terrestrial plants. Its lipid content (2 to 7% of dry weight) containing enough polyunsaturated fatty acids, allowing for heart health benefits. Alternative sources of vitamins (A, C, D and E), minerals (Ca, P, Na and K), polyphenols such as phlorotannin (up to 15% of dry weight) that have antioxidant activities and antimicrobial effects, as well as pigments such as chlorophyll and fucoxanthin with antioxidant capacity. To conclude, *A. nodosum* used as a dietary supplement improves animal health and performance, as well as the quality of animal products (Eleftherios Bonos, 2017). See *Appendix 11*: *Ascophyllum nodosum* **Nutritional** Factsheets.

- *Proteins*

Protein is one of the most interesting algae compounds for breeders. Macroalgae contains all essential and non-essential amino acids in varying proportions, they are a promising source of protein (Linden, 2014). *Palmaria palmata* is used as a new source of protein in animal feed because of its high protein content. Green algae *Ulva lactuca* is also considered an interesting biomass source for animal feed (Linden, 2014).

- *Other interests in animal nutrition*

In addition to their nutritional interest, algae become interesting thanks to their prebiotic, antioxidant, immunostimulant and other effects that are recognized and valued in foods. The benefit of integrating algae into the animal ration can therefore be done on two levels: directly on the health and well-being of the animal or on the quality of the finished product (milk, flesh, egg) (CEVA, 2011). The quality of the finished product is very important for manufacturers who are subject to consumer demand. *Appendix 12* presents a non-exhaustive table of the benefits of certain algae of interest in animal nutrition and the qualities of the finished product.

Health

- *Prebiotic (oligo and polysaccharides) :*

Prebiotics are part of the arsenal of products that ensure the health of livestock, aquaculture and pets. They can then be used as an alternative to antibiotics.

Oligosaccharides and polysaccharides are present in high concentrations in macroalgae and are the basic components of probiotics used to improve animal health. Thanks to their variable structure and functionality, they are exploited as prebiotics. They are used either directly asextracts of algae, or in the form of dietary supplements made from mixtures of algae and other feed ingredients. The oligo and polysaccharides used are fucoidans, laminarin, alginate, carrageenan and their oligosaccharide derivatives (Agasse *et al.* , 2015; Burlot, 2016)

There are many supposed health benefits attributed to the consumption of prebiotics by animals. We can cite: the reduction of pathogen load in animals thus reducing transmission to humans, the improvement of the overall health of animals, increased competence of the immune system, antiviral activity (Agasse *et al.* 2015) , improved stress resistance and improved productivity. (Evans and Critchley, 2014)

For example, adding laminarin and fucoidans to milk fed to piglets (animals that are very fragile at weaning) improves their resistance and allows them to gain weight (Agasse *et al.*, 2015). In Mayotte, fucoidans extracted from the brown seaweed *Sargassum polycystum* have an antiviral action against the white spot syndrome virus that affects shrimp *Penaeus monodon* (CEVA, 2011).

- *Antibacterial properties of phlorotannin*

The antimicrobial activity of phlorotannin is very interesting for animal health. In an environment rich in pathogens, they are thought to bind to bacterial proteins. In intensive pig farms, one of the major challenges is the increasing restriction of the use of antibiotics and metal ions used to combat the predisposition of piglets to contract infections during weaning. Studies have shown that algae extracts are effective in inhibiting several microorganisms, including *Salmonella* or *Escherichia coli.* The structures of phlorotannin and therefore biological activities are different depending on the species of algae used for extraction. The antibacterial properties of phlorotannin of *Ascophyllum Nodosum* brown algae have proven to be powerful and interesting (Ford *et al.* 2020) .

- *Ulvan's antioxidant properties*

Research on the structural and biological properties of ulvan is still in its infancy compared to other marine polysaccharides. However, ulvan is known to have antioxidant properties as well as increased immune system responses of interest to animal health. Research has shown that with only 1% of ulvan added to a complete diet given to hens, an improvement in hen health and egg quality has been observed thanks to antioxidant functions (Kidgell *et al.* 2019).

Environment

In parallel to the prebiotic properties of algae in the modification of the microbiota of the digestive tract, studies have found increases in the digestibility of the whole ration in ruminants fed algal extracts. This has the side effect of reducing methane release into our atmosphere (Evans and Critchley, 2014). Currently, many companies are looking for ways to optimize this discovery and extend it to the world. Thanks to these advances, a reduction in the release of greenhouse gases produced by livestock farms is envisaged.

Red algae A*sparagopsis* has become a high priority for further research and development in this area because of its ability to mitigate enteric methane emissions and potentially generate livestock productivity gains. The discovery of the effectiveness of these algae as an antimethanogenic agent for ruminant production systems is possibly the most promising option to achieve carbon neutrality in the livestock sector in the coming years (Kinley *et al.*, 2020).

Agriculture

Historically and traditionally, macro-algae have been used as fertilizers worldwide in coastal regions with the aim of improving soils (CEVA, 2011) Subsequently, the beneficial effects of algae in agriculture at the soil and crop level have been empirically demonstrated by farmers and numerous scientific studies. The composition of algae is what makes it rich and interesting in this sector. Algae contain interesting nutrients such as macro and micronutrients (nitrogen, phosphorus, potassium, calcium, magnesium, etc.) and significant amounts of vitamins. In addition to providing useful nutrients to plants and soil as fertilizer, algae enhance soil quality, are used in biostimulants, can be used as a biocide to control certain pests and plant diseases, and can serve as chyators in the soil. (Illera-Vives *et al.*, 2020), improving the quality and yields of final crops. Algae are therefore becoming natural resources used as biological inputs and pesticides in line with current market trends towards less industrial chemistry in the food supply (Agasse *et al.*, 2015).

The brown algae *Ascophyllum nodosum*, *Ecklonia maxima* and *Fucus vesiculosus* because of their availability and ease of harvesting, rather than their specificity, are the most used in agriculture. In Europe, seaweed drifting from the coast is most frequently used for agricultural purposes (Illera-Vives *et al.*, 2020).

Biostimulant

A plant biostimulant or Plant Natural Defense Simulator (NDS) is "a substance or microorganism applied to plants to improve nutritional efficiency, tolerance to abiotic stress and/or crop quality characteristics, regardless of their nutrient content" (du Jardin, 2015). Plant biostimulants are prepared mainly from brown algae, such as *Ascophyllum nodosum, Laminaria spp., E. maxima, Sargassum spp*. and *Durvillaea spp* (Illera-Vives *et al.*, 2020). They are considered complementary to fertilizers and amendments because they will not provide significant amounts of nutrients. Unlike pesticides that act directly on pests or pathogens, biostimulants will induce the natural defense mechanisms against infection by a pathogen (virus, bacterium, fungus) or by the attack of a pest. (Agasse *et al.*, 2015). In the framework of Integrated pest management (IPM), advocated by FAO and the European Union, these do not preclude the use of pesticides but helps farmers better target and thus reduce their use. The use of biostimulants may reduce the volume of pesticides applied by 20 to 30%. (Agasse *et al.*, 2015). Biostimulants may also improve a plants' tolerance to salinity, heat and drought.

For several years, seaweed extracts have been available for sale as biostimulants. They are usually used in high dilution spray (1000 times or more). There are many commercial products claiming a protective effect, whose composition, for some, is unknown or which have a dual activity. In general, extracts from algae used as biostimulants are still poorly understood. According to numerous scientific researches, the biostimulating effects come from either growth hormones (auxins, cytokinins, acid), polysaccharides (alginates, laminarins), or trace elements and lipid molecules (sterols) (Agasse *et al.*, 2015; Illera-Vives *et al.*, 2020).

BioPesticide

Algae have a reservoir of molecules with potentially interesting potential as , biopesticides (Agasse *et al.*, 2015). Extracts from brown algae Turbinaria *ornata*, *Turbinaria decurrens* and *Dictyota dichotoma* show insecticide activity. Extracts from *Padina pavonica* brown algae showed antifungal activity (CEVA, 2011).

Fertilizer

Algae are very rich in minerals and nutrients (nitrogen, phosphorus, potassium, calcium, magnesium, sulphide, chlorine, iron, zinc, copper, molybdenum, manganese, and boron) making them a good organic fertilizer providing essential nutrients to plants. Macroalgae is used as a fertilizer in the form of flours or liquid extracts. The European Union has deemed algae suitable for use as an amendment or organic fertilizer for organic production (Illera-Vives *et al.*, 2020).

The majority of the nutrients present are in organic form and must be mineralized to be made available to the plants. The generally low C/N ratio found in algae suggests that they decompose faster than other types of organic manure in the soil. In general, algae have a nitrogen content similar to that of most types of animal manure, a high potassium content, a high content of secondary fertilizers (sulphide, calcium and magnesium) and a lower phosphorus content (CEVA, 2011; Illera-Vives *et al.*, 2020). Nutrient levels differ widely between types of algae, over time and over space. Brown algae contain high levels of calcium and Potassium. Green algae contain important amounts of N, P, Ca, Cu, Zn and B, but are low in Na, Mg, Fe and Mn.

Algae also contain compounds that promote germination, leaf growth, stems and flowering. Studies have shown that the red alga *Padina* and *Asparagopsis taxiformis* improve plant growth as well as plant quality (CEVA, 2011). Algae contain no known pathogens and do not spread terrestrial weeds.

Improved soil quality

Phycocolloids, alginic acid, and enzymes in algae improve soil structure. Phycocolloids are used to retain water to make it available to plants. Ca and alginic acid can warm the soil. Phycocolloids, alginic acid, fucoidan and, methionine increase the bioavailability of certain nutrients. (Illera-Vives *et al.*, 2020).

Algae have been shown to have a positive effect in the capture of heavy metals to clean up polluted soils. You still have to be careful because soil that receives an algae full of heavy metals can be transmitted to the soil, causing soil contamination. The algae must therefore come from unpolluted sites for agricultural purposes (Illera-Vives *et al.*, 2020).

Others

Biofuel

A biofuel is a fuel that is produced from biomass. Seaweeds and other plants can be converted into biodiesels (Van Iersel *et al.*, 2009; O'Connor, 2011). The production of "algofuels" involves the fermentation of seaweed carbohydrates. Some macroalgae have high carbohydrate levels that can be used for bioethanol production (Kraan, 2016). The brown algae *Saccharina Latissima* is the most commonly used species for the production of algofuel.

Biogas

Biogas is the gas produced by the fermentation of organic matter in the absence of oxygen through a four-step process, which includes hydrolysis, acidogenesis, acetogenesis and methagenesis (Tiwari and Troy, 2015). Biogas can be used to produce electricity but also as a clean renewable fuel for transport vehicles, in fuel cells or in waste management for agriculture (Biogasman, 2019). Macroalgae can be used to produce biomethane because they contain little cellulose and no lignin and therefore undergo more complete hydrolysis (Hughes *et al.*, 2012).

Bioplastic

Bioplastics can also be produced from poly saccharides in plants, bacteria and green or brown algae. Bioplastics from seaweed can be found in the following categories: packaging industry, catering products, gardening, medical products, and automobiles (Rajendran *et al.*, 2012). A recent patented packaging material technology incorporates agar as a modifying agent. Made from agar and other natural raw materials, these new packaging materials are durable, biodegradable and are an alternative to plastics (WALSEA, 2020).

Textiles

Alginate thickeners are used in textile printing to prevente dye migration and obtain sharp, clean drawing patterns. (Fijan, Šostar-Turk and Lapasin, 2007). They chemically combine with cellulose in the tissue, but do not react with dyes, unlike many usual thickeners such as starch, which eventually result in a loss of color. In addition, they clean easily from textiles (McHugh, 2003). Alginates contained in *Ascophyllum nodosum* that are mainly used to fix the dye.

Macroalgae pigments such as chlorophyll, carotenoids, phycobiliproteins, beta-carotene and lutein are also used for the extraction of natural dyes in textiles (Janarthanan and Senthil Kumar, 2018).

Finally, it is possible to make fabric with the fiber contained in algae. Nanonic Inc. has developed SeaCell, a compound of brown algae fiber *(Ascophyllum nodossum).* Cellulose is dissolved in a solvent containing water and then after washing and re-cleaning, the solution is filtered and passed through chains to give filaments (Ross, 2017).

Antifouling

Biofouling of marine installations costs billions of US dollars for the maritime industry and navies around the world. Most antifouling technologies use toxic biocides, like copper, that kill organisms and accumulate in the environment. However, many marine algae remain clean over longer periods of time, suggesting their strong antifouling potential. Researcher discovered many isolated substances with potent antifouling activity, among them belongs fatty acids, lipopeptides, alkaloids, steroids, terpenoids etc. (Dahms and Dobretsov, 2017).

Carbon sequestration

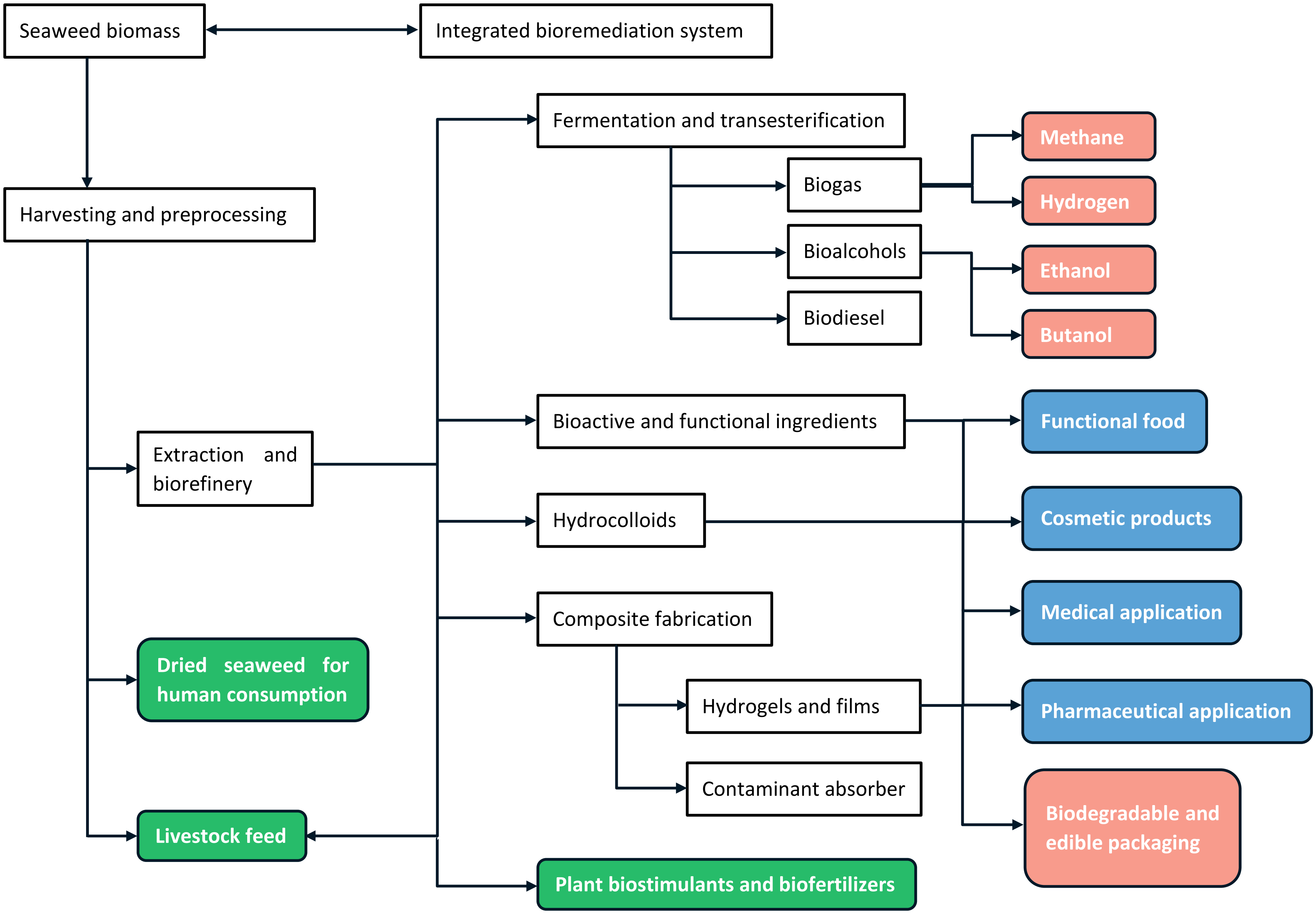
Macroalgae use carbon dioxide from the environment through photosynthesis to produce biomass (Erlania and Nyoman Radiarta, 2015). Carbon dioxide is the most commonly produced greenhouse gas (GHG). Carbon sequestration is defined by United States Geological Survey as the process of capturing and storing atmospheric carbon dioxide. It is used reduce the amount of GHG in the atmosphere and oceans with the goal of mitigating or deferring global climate change. From this emerged the carbon credit market. It is a market destined for countries and companies who wish to compensate for the environmental impact of their activity by investing in projects that capture carbon emissions.

Trees and algae naturally sequester carbon dioxide, but algae can consume more carbon dioxide than trees. They can cover more area, grow faster and be more easily controlled by bioreactors (Lamm, 2019). In addition, the algae-based $CO2$ mitigation strategy has the potential to obtain valuable products at the end of the process.

Conclusion

The list of compounds in this study is by no means exhaustive, but it covers the main active components of algae as well as a large part of the range of their biological activities. This part has highlighted the great versatility of algae that promise them an important place in many sectors. Whether consumed directly as an ingredient, additive or dietary supplement by humans or animals, seaweed has compounds with bioactive properties that are very promising for health. Its versatility prevails even in the most unexpected sectors such as textiles, biofuels, or explosives. This bibliographical review makes it possible to realize the inexhaustible richness of this resource, but what about the trends in demand related to this product?

Figure 3: Utilization of seaweed in food and non-food application



Source: Adapted from Padam and Chye, 2020

Table 4: Utilization of seaweed component by sector

Seaweed main component			Food: Direct	Food: Additive	Medicinal Pharmaceutical	Nutraceutical	Cosmetics	Animal feed and health	Agriculture	Other
Polysaccharides		Carrageenan	■	■	■	■	■	■		
Polysaccharides		Alginates	■	■	■	■	■	■	■	■
Polysaccharides		Agar	■	■	■	■	■	■		■
Polysaccharides		Fucoidan	■		■	■	■	■		
Polysaccharides		Ulvan	■		■	■	■	■	■	
Polysaccharides		Laminarin	■		■	■	■	■		
Polysaccharides		Furcellaran	■	■	■				■	
Polysaccharides		Mannitol	■	■	■	■				■
Polyphenols		Flavonoïds	■		■	■	■			
Polyphenols		Bromophenols	■		■	■	■	■		
Polyphenols		Terpenoids	■		■					
Polyphenols		MAAs	■	■	■	■	■	■		■
Polyphenols		Phlorotannins	■		■	■	■	■		
Pigment		Chlorophyll	■	■	■	■	■			
Pigment	Carotenoids	α-carothene	■	■	■	■	■			
Pigment	Carotenoids	β-carothene	■	■	■	■	■			
Pigment	Carotenoids	Anthéraxanthine	■	■						
Pigment	Carotenoids	Fucoxanthin	■	■	■					
Pigment	Carotenoids	Lutéine	■	■	■					
Pigment	Carotenoids	Violaxanthin	■	■						
Pigment	Carotenoids	Zeaxanthine	■	■	■	■	■			
Pigment	Phycobilili-protéines	Allophycocyanine	■		■					
Pigment	Phycobilili-protéines	Phycocyanine	■	■		■	■			
Pigment	Phycobilili-protéines	Phycoérytrhine	■		■	■	■			
Proteins			■	■	■	■	■	■		
Vitamins			■	■	■	■	■	■		
Lipids		PUFAs	■		■			■		
Lipids		Stérols	■		■					
Mineral			■	■	■			■	■	

Source: Based on all the literature review above

II. Current and future demand

A. Interview methodology

For this research project, we conducted a telephone survey of sector actor in the seaweed industry to explore in greater detail the future of the markets described in Section I. Three types were identified: producers, algae-using industrialists, and scientists. The establishment of a contact list identified the persons representing the actors in these three samples. They were then contacted by email to offer them an interview. Of the more than 200 people contacted, about 20% responded to the team, and just over 10% agreed to conduct an interview.

Table 5: Sampling table of the study

	Size of the sample	Country	Industries/Markets
Producers	4	France, Portugal, Sweden, Madagascar	Seaweed selling
Scientists	10	Canada, Indonesia, Portugal, Ireland, and England	Research
Algae-using industrialists	6	France, Ireland, India, and Denmark	Food, Animal feed and health, Textile, New Technologies, Agriculture, Health

Total of interviews: 20

Less formal interviews were also conducted with others as resource persons (specialists in the seaweed market, association member, professors, etc.). These individuals were able to guide the team in its bibliographical research and provided a global view of the algae sector, particularly its historical evolution.

Interviews were conducted on different video conference platforms (Skype, Zoom, etc.), as well as by phone and in-person when the interviewee was in the geographic area of a team member. If agreed upon, a recording of the conversation was made to carry out a word for word transcript afterwards, otherwise a real-time transcript was conducted. The transcripts were then manually coded on the software named Dedoose in order to identify trends in the perception of the demand by the different actors of the global seaweed market. The data was collected on the basis of data saturation of a qualitative survey. More specifically, the interviews were coded throughout the interview phase and were supposed to stop once the saturation of ideas, meaning no new ideas were emitted by newly interviewed actors, was reached. Due to a low response rate and mandatory deadlines established by the school, the team hasn't been able to carry out the interviews to a sufficient extant in order to obtain saturation as wished.

Dedoose software coding pointed to trends in current and future algae demands of some industries, as well as some algae compounds and species. Other trends in the outlook for demand in different markets have also emerged.

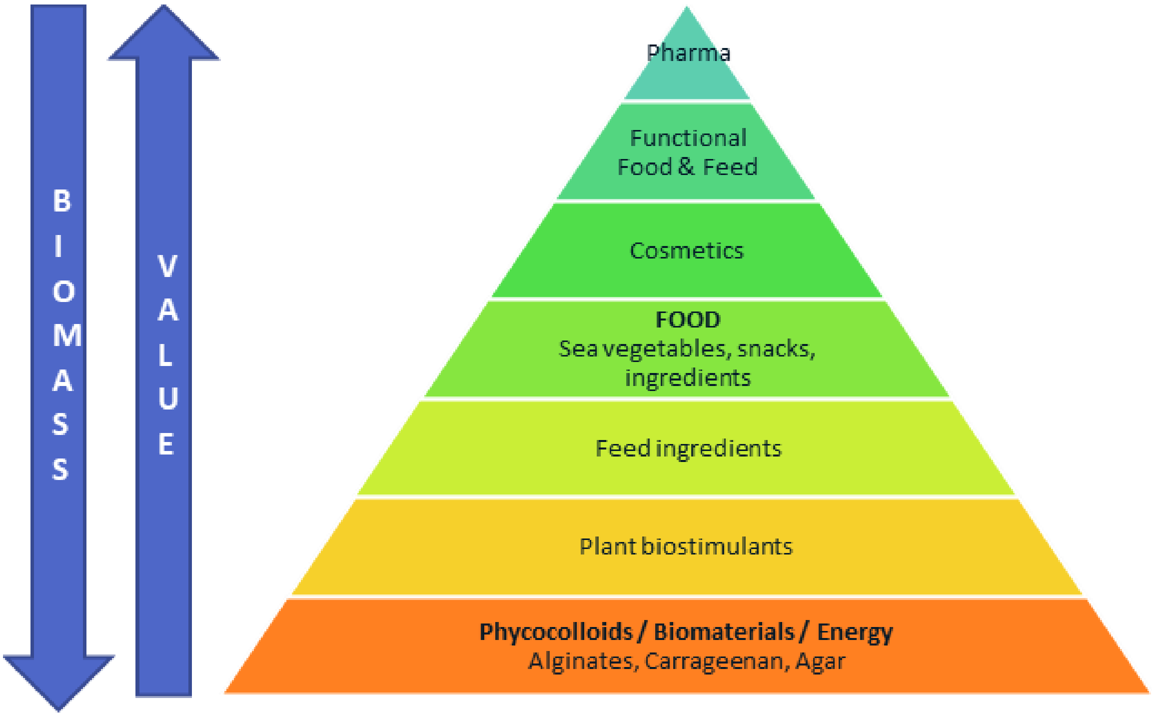
Presented in this part is the data that the team has collected, both through the bibliographical research and through the interviews on the demand for seaweed. These data were cross-checked and compared to each other according to their different type of sector actor, and their analysis are developed in the part "Discussions" just after this one. This allowed the team to analyze some changes in demand in the short and medium term, as well as some future prospects for the global seaweed sector.

The methodology of the interviews and of data collecting was based on that of two qualitative studies: Evans *et al.*, 2017 and Tapera *et al.*, 2019. They also sought to identify trends among data collected from samples of interviewees. Similarly, they followed the saturation principle and used the Dedoose software to code and classify data.

B. Demand trends

As a very versatile biomass, seaweed has a wide range of species that can be broken down into an extensive number of components with many different uses. In 2012, humans consumed 40% of global seaweed production whole and another 40% indirectly through processed foods. The remaining 20% were used in a range of industrial applications (FAO, 2014; Loureiro, Gachon and Rebours, 2015). Interviews and literary research have permitted to identify current markets such as uses in food and human nutrition, nutraceuticals, animal nutrition and health, plant bio-stimulants, cosmetics and pharmaceutical applications. These sectors differentiate mostly in terms of volumes used, value-added from its products, potential from research and development, and marketing. Value-added can be roughly explained by *Figure 4*. This section briefly presents the demand's trends in each sector.

Figure 4: Value according to biomass



Source: From Markets and Markets, 2020

Demand by industry

Food and human nutrition

The seaweed food market is a sector characterized by large volume and low value-added. It can be described as the low hanging fruit of the seaweed industry. Indeed, little to no processing is necessary for direct consumption. As for indirect consumption through food additives, markets like the phycocolloid sector are already well established with cheap production costs and large biomass availability.

Consumption levels are not well characterized now as there is a lack of data. However, it was estimated in 2018 that 85% of the seaweed was consumed directly or processed into food products (FAO, 2018) An increase from the 80% estimated in 2014 (FAO, 2014). This demand differs greatly according to the geographical location. Demand for fresh and preserved forms, including dried seaweed for direct consumption, is largely limited to the East Asian markets and wherever Japanese cuisine exists elsewhere in the world (FAO, 2020). In Europe, the market for edible seaweed is expected to grow at a 7 to 10% rate according to a Building Information Modeling (BIM) market study dating back to 2014. This is what companies like Kosteralg in Sweden are counting on. This company works with Michelin Star restaurants to advertise seaweed dishes and sell their locally produced and organic certified seaweed. Even so, a study of the French consumption of edible seaweed still characterizes it in Europe as “a food of ‘dearth’, since it does not enter into food customs” (Le Bras *et al.*, 2014)**.**

On the other hand, indirect consumption is an industry-driven and growing sector of the seaweed market. Phycocolloids have had a far-reaching impact in the global food market. IMR International, a hydrocolloid information center, estimated the market for phycocolloids* () at 87 000 tons per annum and USD 1101 million in 2018. Carrageenan, compared with agar and alginitic acid, is the most widely used, representing 57 000 tons of that sector alone, but less than half in terms of the value. Current annual growth rate*(***Erreur ! Source du renvoi introuvable.***) is estimated at 2.2 % for carrageenan, 2.0% for agar and 2.6% for alginates. While the large markets at present are the European Union and the United States of America, demand for carrageenan is growing, particularly in non-producing countries (FAO, 2020)**.**

Table 6: Food Hydrocolloid Market 2018 [1]

Hydrocolloids	‘000 T PA	$ Million	% Value	% Volume
Starches	1,640	1,407	19.4	70.2
Gelatin	217	1,354	18.7	9.3
Pectin	70	1,247	17.2	3.0
Xanthan	91	638	8.8	3.9
Carrageenan	57	522	7.2	2.5
Alginates	17	314	4.3	0.7
Gellan	6	278	3.8	0.3
Agar	13	265	3.7	0.6
Locust Bean Gum	13	236	3.3	0.6
*CMC**	49	217	3.0	2.1
Arabic	57	186	2.6	2.4
*MCC***	16	129	1.8	0.7
*MC/HPMC****	11	123	1.7	0.5
Guar	64	116	1.6	2.8
Other	13	212	2.9	0.6

*Carboxymetylcellulose **micro crystalline cellulose ***hydroxypropylmethylcellulose

***Source:** Adapted from IMR international, 2019

Total	2,334	7,244	100	100

Table 7: Annual Growth Rate[1]

Hydrocolloid	AGR %
Gellan	**8.5**
MC/HPMC	**6.8**
Pectin	**5.1**
Guar	**4.8**
Xanthan	**4.5**
MCC	**4.5**
LBG	**3.3**
CMC	**3.3**
Alginates	**2.6**
Arabic	**2.6**
Carrageenan	**2.2**
Agar	**2.0**
Starches	**1.6**
Gelatin	**1.3**
Other	**3.5**

Source: Adapted from IMR international, 2019

This industry, for both direct and indirect consumption, was one of the most mentioned by interviewees, all types combined. Two of the industrialists agree that the demand for seaweed in this industry is currently very high. Three industrialists and a French producer believe that demand will only increase in the short and medium term. The producer justifies his estimate by the fact that his business to consumer sales of fresh seaweed have increased each year by 5% over the last ten years. According to him, this increase is since more and more people in Europe are interested in algae in direct food (without processing). However, three of the interviewees confirmed that European demand for algae is mainly geared towards the nutritional properties of algae in an indirect diet. One scientist pointed out that over the past 30 years, the focus of European experiments involving algae has focused on their texturing properties and that currently the majority of European algal biomass is used for these purposes. One producer points out that although some European countries such as France have good algal resources, there are still few being exploited for direct food applications.

In terms of texture agents, three of the interviewees (two industrialists and one scientist) agree that the availability of alginate on the market does not meet the current demand. A scientist explained that the natural resources from which alginates are currently extracted do not allow to have more than 60k tons per year and thinks that it will not go beyond that. Imports of seaweeds less rich in alginates need to come compensate the current stock of highly concentrated algae as it represents the limiting factor of the industry. Two of the interviewees (one industrialist and one scientist) estimate the current demand for carrageenan was to increase. According to one, the limitation on the increase in demand is mainly due to competing products of carrageenan, such as xanthan, bad press, price volatility and limited supply of wild species.

A key international player, industrialist in carrageenan processing and trading, mentioned the demand for plant-based protein as a factor pushing the demand for hydrocolloids as texture agents to agglomerate the ingredients. They believe that there is a possibility to develop applications from these new trends.

Regarding the geographical distribution of this demand for algae in the agri-food industry, three of the interviewees confirmed that Asian demand is more specifically geared towards direct consumption of seaweed. The European demand focuses on the nutritional values of algae, but as an indirect consumption (processed product). This European reluctance to eat seaweed has been explained by four of the actors as a factor of cultural influence, as mentioned above.

[1]IMR International have excluded China for data accuracy purposes.

Nutraceuticals and dietary supplements

The nutraceutical market is comprised of dietary supplements, functional food, and beverages. The global nutraceutical market size was valued at USD 382.51 billion in 2019 projected to reach USD 722.49 billion by 2027 (Grand View Research, 2020) compared to USD 250 billion in 2014 (Suleria *et al.*, 2015). This sector is expected to expand at a CAGR of 8.3% between 2020 and 2027 (Grand View Research, 2020). Seaweeds are the most popular type of algae in the nutraceutical industry as it is an important source of essential nutrients and new bioactive molecules for human nutrition. The market segment for nutraceuticals saw a great evolution between 2014 and now. Europe and the USA held 85 % of the market share back in 2014. More recently, the Asia-Pacific region became the single leading market with 31.01 % of total share and is expected to keep the lead up until 2027. This can be explained by an increase in revenue and an evolution in eating habits due to a transition towards healthier lifestyles in emerging economies (Grand View Research, 2020).

These forecasts prove to be favorable for the development of the seaweed industry and the presence of key international players point in that direction. These corporate industry participants include Cargill, Archer Daniels Midland, DuPont, Nestle S.A, Danone, General Mills, Innophos, WR Grace, and Amway.

However, seaweed volumes utilized in this market segment are not well known. There is also an issue in differentiating what we call functional food from just food. Indeed, functional food is said to have accounted for the largest share of the nutraceutical market in 2019 and generated revenue of USD 187.51 billion (Grand View Research, 2020). Notwithstanding these numbers, it is important to determine whether whole seaweed or only extracts are accounted in the functional food market. As mentioned before, demand for whole seaweed differs greatly according to the geographical location and characterizing the form under which these nutraceuticals are consumed may alter these projections. Moreover, the nutraceutical market is a segment of the human nutrition market that relies greatly on the marketing of the products because the popularity of its products is often psychological or social in nature.

This industry has been very little cited in interviews or could be associated with the European's interest for nutrition as mentioned in the above section 'Food and Human nutrition'. Nevertheless, this sector may be more interesting in terms of its development potential than that of pharmaceuticals.

Animal nutrition and health

Seaweed stimulates food intake and growth, while decreasing the amount and cost of protein, especially fishmeal, in diets. (World Bank Group, 2016)**.** Other than growth, seaweed intake is being studied to better animal health. Addition, studies have demonstrated methane reduction when fed to cattle. (Maia *et al.*, 2016)**.** The Seaweed Company, Inc. formulates and markets blends using bioactive ingredients from seaweed to enhance immune system function and digestive health. It can be read on their website that the desired outcomes of these products' use are "antibiotics reduction, methane and nitrogen emission reduction, more milk, better feed efficiency, higher fertility and reduced mortality for cows, pigs, poultry, horses, dogs & cats."

The market for functional feeds or feed additives is projected to grow from USD 33.0 billion in 2018 to USD 44.3 billion by 2023, at a CAGR of 6.1% during the forecast period (Markets and markets, 2019)**.** According to Technavio, a market research and advisory company, the algae-based animal feed, and ingredients market itself, is poised to grow by USD 1.13 billion during 2020-2024, progressing at a CAGR of over 8% during the forecast period.

The feed and animal health sector have been present on the market for over 15 years, however several factors are influencing its growth. It can be primarily attributed to growing livestock and an increasing demand for meat products by consumers. The yearly worldwide need for chicken close to 90 million tons, and the poultry industry has tremendous interest in alternative sources of feed that is likely to grow further. As an affluent protein source and other nutrients, prospects for the market development of the macroalgae are expanding everywhere throughout the world (Future Market Insights, 2019)**,** even more so with a growing public interest for environmental issues.

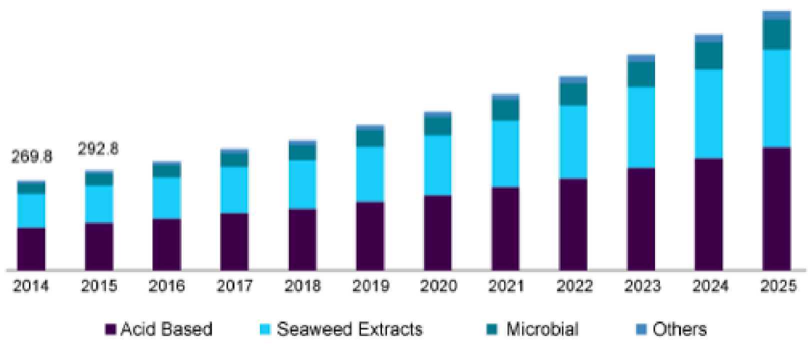
Two of the industrialists surveyed, having a share of their activities in the food and animal welfare sector, use the concept of "growing market" to talk about this industry. Current demand is important according to them. One of them explains that his company's products meet a majority demand from breeders who want to reduce antibiotics in their breeding techniques, which he says is a big fear today. The other industrialist explains that this same demand is included in an even wider consumer demand for healthier products. Products used in the animal feed sector, such as antibiotics and antivirals, are mainly of microbial origin and sometime chemically synthesized. (Villa et al., 2017) Seaweeds, having an antibiotic and viral inhibitory activity, can help reduce their use.

Two of the researchers agree that this industry has a strong potential for development in the short to medium term. According to them, the extensive research in this area justifies this potential. A French seaweed producer explained that he was selling part of his production to the research industry, particularly for study topics concerning the benefits of algae for cows.

Plant Bio-Stimulants

In agriculture, seaweed has been used in soil fertilizers because of its rich plant nutrients (e.g. potassium, nitrogen and phosphorus) (FAO, 2018). However, the plant bio-stimulant (PBS) market is quickly developing as it can provide an environmentally friendly alternative to fertilizers and pesticides. Plant bio-stimulants, as defined in the previous section, are any substance or microorganism applied to plants with the aim to enhance nutrition efficiency, abiotic stress tolerance and/or crop quality traits, regardless of its nutrients content (Du Jardin, 2015.) The PBS market is estimated at USD 2.6 billion in 2019 and is projected to reach USD 4.9 billion by 2025 at a CAGR of 11.24 % between 2017 and 2025 (Markets and markets, 2019). Similarly, Grand View Research and Fortune Business Insights, 2019, project a USD 4.14 billion market for plant bio-stimulants by 2025 at a CAGR of 10.2 %, and USD 2.50 billion in 2019, projected to reach USD 5.35 billion by 2027 at a CAGR of 10.65 % over the forecast period.

Figure 5: Projected U.S. plant bio-stimulant market size, by source, 2014-2025 (USD Million)

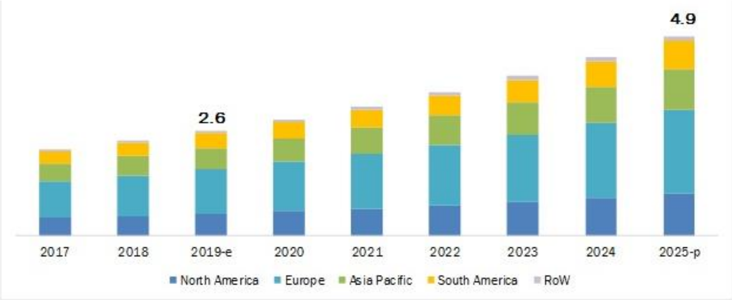


Source: Grand View Research, 2018

Seaweed extracts (SE) constitute more than 33% of the total PBS market worldwide and are predicted to reach a value of EUR 894 million (~~USD 1064 million) in 2022 (Boukhari *et al.*, 2020). A North Sea Farm Foundation market study supports these forecasts: the seaweed-based PBS market was about EUR 483 million (~USD 575 million) of the global PBS market in 2016 and is projected to reach EUR 894 million (~USD 1064 million) in 2022. This market segment is projected to grow at a CAGR of approximately 11%. The market is primarily driven by strong demand for high-value crops across the globe and the increasing need to support crop growth due to abiotic stress, arising from changing climatic conditions.

Although PBS have been on the market for 20-25 years it is likely to boom in the years to come. The term PBS is new and so is the market it represents. Indeed, "Currently PBS are considered as a full-fledged class of agri-inputs and highly attractive business opportunity for major actors in agroindustry. As the dominant category of the PBS segment, SE were key in this growing renownd" (Boukhari *et al.*, 2020).

Figure 6: Biostimulant Market, By Region (USD Billion)



e - Estimated; p - Projected

Source: Markets and markets, 2019

Table 8: PBS market shares

Region	Market value 2016 (mln EUR)	Percentage of total (%)	Projection market value 2022 (mio EUR)	Percentage of total projection (%/y)	CAGR (%/y)
Europe	194	40,1	369	41,2	11,1
Asia-Pacific	124	25,8	245	27,5	11,6
North America	74	15,4	122	13,7	8,4
South America	68	14,2	119	13,3	9,4
Rest of the world	22	4,5	39	4,3	9,7
Total	**482**	**100**	**894**	**100**	**10,5**

Source: North Sea Farm Foundation, 2018

Europe is a major producer of row crops and the North Sea Farm Foundation study shows that almost 40% of the total amount of land area treated with seaweed PBS is used to produce such crops, of which 23% are fruits and vegetables. This can explain Europe appearing as the largest market of seaweed-based PBS in Figure 12 and Table (your "figure") 13. However, the global PBS market is growing at a CAGR of about 10%. With a growing population in Asia, increased use of fertilisers and usage of chemical pesticides as farmers try to maintain productivity is progressively degrading soil quality. Furthermore, the threat of climate change is looming large over agricultural production in this region (Chew and Soccio, 2016) giving growth perspective to the PBS market there.

The PBS market is focused on large quantities since almost all the algae is used. This market can therefore include quantities of algae that the fine chemicals market cannot consume.

Two industrialists and a scientist talked about a promising future for algae in the PBS industry. According to them, the current demand for this type of seaweed-based product is not being met by supply, and this shortfall is expected to increase in the short to medium term. One of them even points out that recent studies show that this is a fast-growing sector (two digits) and that it will continue to evolve like this in the next 5 to 10 years due to the rise of abiotic stresses, as previously mentioned. Another confirms that public interest for natural solutions is also a growth factor.

A key international industrialist in animal health & nutrition and plant care, noted that despite working with large quantities, the value-added from these products remained very high.

Cosmetics

The cosmetics market is characterized by low volumes of bioactive ingredients with very high value-added. Skincare alone is estimated at USD 145.2 billion in 2020 (Shahbandeh, 2020). Seaweeds are often used in care products to affect their organoleptic properties, its stabilization and preservation, and also have bioactive compounds which fulfil a real cosmetic function and activity (Bedoux *et al.*, 2014). In 2018, the global cosmetic market grew an estimated 5.5 % in comparison to the previous year. Skincare is the leading category, accounting for 39 % of the global market, and is forecast to remain the most profitable. Hair care products made up a further 21 %. Niche sectors, such as natural/organic cosmetics rapidly gained market share with eco-consciousness and cause-based consumerism (Shahbandeh, 2020).

This industry is one of those on which the interviewees were the most in agreement. Indeed, six of them agree that the demand for seaweed in this sector has a strong growth potential in the short and medium term. They mostly justify this potential by the multitude of active ingredients present in algae that can be applied to the design of cosmetic products. Among these active ingredients were cited some pigments, such as carotenoids, lipids and polyphenols. According to these players, the current demand is more specifically directed towards algae whose properties would allow the design of cosmetic products with moisturizing, foaming (tensio-active), anti-age, UV protection and skin whitening properties. Three of the players interviewed (two industrialists and one producer) said they were working with the cosmetics industry on research and development projects related to algae. However, they did not elaborate because of proprietary information issues. It is the choice of active products that allows companies to stand out in this sector. The race for innovation is therefore a way for them to influence demand and remain competitive.

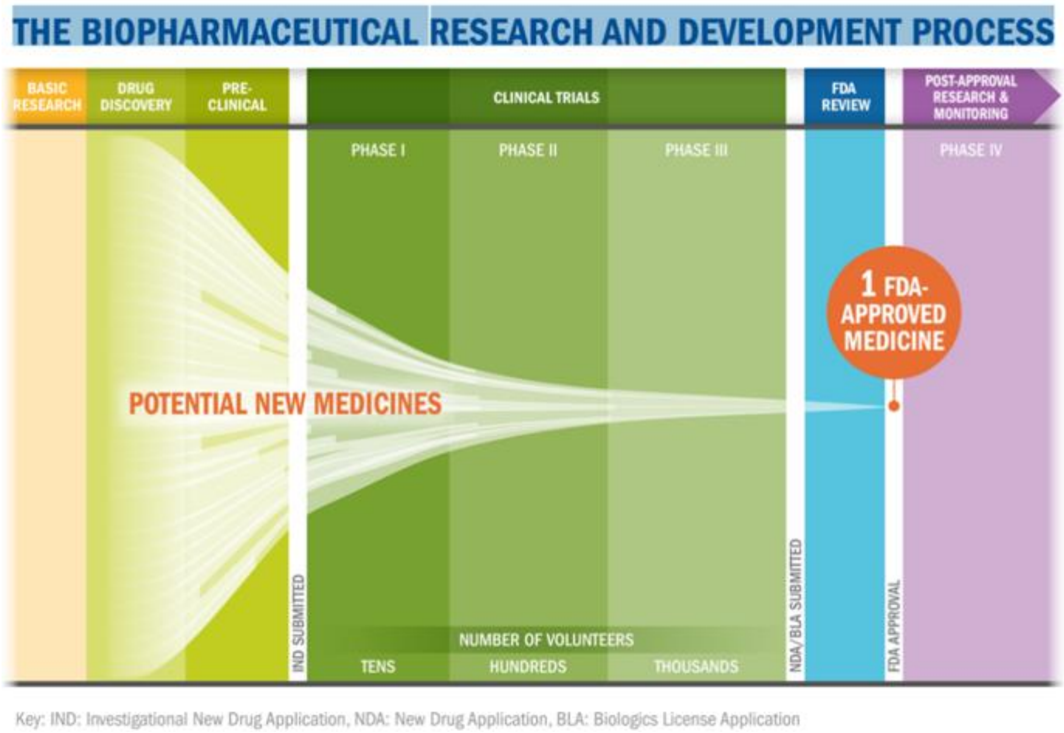
Pharmaceuticals

The relatively new seaweed market in pharmaceuticals is currently based on their use as texturizing agents delivered by phycocolloids. It is therefore very difficult to quantify seaweed use in the pharmaceutical sector as they play a minor role in the composition of medicine. Internationally, the place of seaweed in pharmaceuticals is low around the globe as no world-class progress has been made (most recent scientific paper dates back to 2004).

Nevertheless, interviews and literature have shown that components of interest for this industry are to be found in seaweed (polyphenols, pigments, fucoidan, etc.) (Smit, 2004). Most species of algae have antioxidant power, representing very promising prospects for further development. Additionally, public awareness for the use of sustainable and natural resources rather than potentially harmful synthetic products is on the rise. Likewise, overuse of antibiotics has led to the need of new antibiotics, effective against new resistant bacterial strains (World Health Organisation, 2020).

Still, prospects for development are hampered by regulations. Whereas it takes up to one year of proof before the product can be in the personal care section of pharmacies, a new medicine or drug will take on average at least 10 years from initial discovery to the marketplace, with clinical trials alone taking six to seven years on average. Considering the cost of unsuccessful drugs, the average cost to research and develop each successful drug is estimated to be USD 2.6 billion. The overall probability of clinical success is estimated at less than 12% (PHRMA, 2015). Investors have very little interest in investing in low-paying research in the short term.

Figure 7: The biopharmaceutical R&D process



Source: PHRMA, 2015

A related issue posed by seaweed sourced molecules is their uniformity in terms of quality. Pharmaceutical labs prefer working with a uniform molecule whereas the parameters of algae cultures are, for the most part, not controlled, preventing uniformity of compounds. For this reason, many companies turn to synthetic chemistry to recreate natural molecules.

Five of the players (two industrialists, two scientists and one producer) share the same opinion on the potential for developing demand in this market. Indeed, the future of seaweed in this industry is, according to them, hindered by too many factors. Three of them justified this opinion by the constraints imposed by the legislation in this area. In particular, as mentioned above, the long stage testing constraint that products must pass before they can be put on the market. The second reason for this opinion is the question of profitability. Synthesizing a molecule generally costs pharmaceutical companies much less than extracting a molecule from plant biomass.

An expert scientist in seaweed believes that the medical sector that will generate large volumes of algae will be the health nutrition sector (nutraceuticals). Rather than being used as a curative treatment, the current knowledge of seaweed components will be used in preventive treatments.

New applications and emerging markets

Biofuels

Seaweeds can offer a yield of 2 to 20 times higher than existing raw materials for biofuels, compared to corn, sorghum and beet. Which may offer new avenues for growth for the industry (Emerging Markets Online, 2020)**.** This market is likely to absorb huge quantities of seaweed biomass. Increased R&D by some major oil and gas companies and university-led research consortia is expected to propel production over the next few years (period projected to 2025). For example, USD 10 million from the multinational BP (British Petroleum, a company extracting, refining and selling oil) was granted to the experienced seaweed producer, Martek (Emerging Markets Online, 2020)**.** The global algae-based biofuels market size is expected to reach USD 10.73 billion by 2025, according to a new report from Grand View Research, Inc.. Transportation is expected to account for 70% of global demand by 2025 and is therefore expected to dominate the algae-based biofuels market, due to its high potential for replacing diesel and gasoline in motor vehicles. For example, in 2010, the US company Solazyme, Inc. delivered over 36,000 litres of 100% micro-algae-derived biofuel to the US Navy. This test was a key step towards the commercialization of the product and its certification.

The Asia-Pacific appears to be a key market due to the rapid growth of the auto industry. The presence of large economies such as China (one of the top 5 producers of algae biomass) is expected to stimulate demand for sustainable energy resources. China has made significant investments in the production of energy derived from algae such as diesel, gasoline and hydrogen (Grand View Research, 2017). The biggest limit of this energy source is the cost of production. Therefore, research is increasing to reach economic viability. Major players in the algae biofuels industry include Algenol, Blue Marble Production, Solazyme Inc., Sapphire Energy, Culture Biosystems, Origin Oils Inc., Proviron, Genifuels, Algae Systems, Solix Biofuels, Algae Production Systems and Reliance Life Sciences (Grand View Research, 2017).

Four interviewees (two industrialists and two scientists) share the same opinion regarding the future of this market. According to them, it will not be economically profitable for a good ten years. This is due to technological constraints in extraction, the amount of algal biomass required for production, and the lack of in-depth knowledge of the biology of the vast majority of the species. One of the scientists thinks that the future is more on the side of microalgae for this application.

A key international player, industrialist in seaweed biotechnology, believes that bioplastic will be fully commercialized in about four years, and biofuels between five and six years from now. Seaweed is not only 100% biodegradable but also does not generate new carbon dioxide. It should therefore be a sustainable and scalable raw material in the near future according to this interviewee.

Bioplastics

Like biofuels, the bioplastics market could absorb huge quantities of seaweed biomass. The global bioplastics & biopolymers market size is expected to grow from USD 10.5 billion in 2020 to USD 27.9 billion by 2025, at a CAGR of 21.7% during the forecast period (Markets and markets, 2019). Seaweeds have more potential than land-based biomass sources because of its high biomass, ability to grow in wide range of environments, cost effectiveness, ease of cultivation in natural environments and it can be harvested year-round (Rajendran *et al.*, 2012). The technology still has to develop: Prices are currently too high. Bioplastic packaging faces adaptability issues in developing countries because of lower consumer incomes, incompatibility of bio-resin with traditional plastic packaging machines, and higher labor and processing costs compared with traditional petroleum-based plastic. (Future Market Insights, 2018).

One of the scientists and one of the industrialists interviewed believe that bioplastics is currently a promising and expanding market. Many companies are embarking on the development of materials, especially for packaging or textiles, but are not yet on products made 100% from seaweed. The technological lag in relation to the design idea is therefore currently a hindrance to the development of this market. The current innovations come rather for materials of hybrid composition. One of the major constraints that these companies encounter is once again their need for biomass.

C. Development challenges & factors influencing demand

The applications of seaweed are multiple and their potential for development in some industries numerous. Many of the stakeholders interviewed raised multiple development issues currently facing the algae sector. Trends were extracted from the interviews and allow us to understand what levers to raise today to enable a better development of the sector and its industrial applications.

Production limiting factors

"Today the big bottleneck is the ability to produce large volumes at a reasonable price," (industrialist in carrageenan processing and trading).

Six of the interviewees (three scientists, two industrialists and one producer) spoke of the shortage of high quality raw material as the biggest issue in the seaweed sector. Many European companies currently base their exploitation on wild seaweed, as the cultivated seaweed is too expensive. However, collected seaweed are very sensible to climatic hazards rendering the supply inconstant.

Improve knowledge of seaweed biology, markets and technology

"We need to increase the workforce. That is to say that beyond the act of production, we need a human ecosystem formed. We need biologists, chemists etc.," (expert scientist in seaweed).

The lack of basic knowledge of seaweed biology is the second most raised point by the interviewees. The same six actors stressed that in order to be able to diversify sourcing into algal biomass, a knowledge of the biology of these algae (life cycle, reproduction, etc.) as well as their production techniques are necessary. Two stakeholders talked about initiatives and projects launched by some companies that are trying to gather this data. A Canadian scientist explained that currently in the USA, companies are developing large research programs that involve universities to develop different aspects of culture, including genetic mastery and life cycle control. Engineers would also be involved in trying to mechanize culture operations. In France The Roscoff Biomarine Institut and the Olmix company have teamed up with La Sorbonne University to specifically train experts in algae biotechnology to train 100 people a year, in addition to a technical branch in association with a large French research center. One of the interviewees points out that currently many people are interested in the seaweed markets and its applications, but lack the expertise to gather the necessary data.

Standardization of quality and traceability

"A major issue faced by the seaweed industry, like many products of natural origin, is homogeneity. Producers are going to have a seasonality. Therefore, a processor producing at a specific moment from a batch, is not said to find exactly the same assets from another batch 3 months later," (seaweed extract and ingredients industrialist).

Five of the players (three industrialists and two scientists) speak of raw material variability as one of the challenges of the global seaweed industry in the coming years. The quality and traceability of seaweed biomass is heterogenous and insufficiently controlled, holding back companies from purchasing from certain sources. Indeed, quality control is not systematic. For example, algae with strong absorbent properties may contain high concentrations of heavy metals or other toxic substances absorbed from their environment. The supply chain is often made up of many intermediaries. One of the industrialists working with carrageenans gives the example of their supply chain where small producers sell their algae to intermediaries. The chain can include several collectors, wholesalers, suppliers, etc. until the receipt of the product by the processors. Some companies are therefore looking to standardize higher quality and traceability by developing producer cooperatives and the implementation of their own quality control and monitoring protocols. This initiative also allows them to buy directly from the cooperatives and thus to shorten the supply chain.

Improving technology

"The market is changing, so everything upstream must also evolve," (expert scientist in seaweed on the subject of technological improvement).

Most interviewees pointed to the need for improved extraction, purification and other processing technologies. The bioplastics industry is the most dependent on these improvements.

Capturing value from everything that is present in seaweeds

"When people start extracting one component I would say: what about the rest, if you can use that also you can use it all", hydrocolloid specialist.

Five of the players interviewed spoke of an improvement in the value-added of seaweed, in all industry sectors, as an important issue to be addressed. According to them, the sectors where currently seaweed has the most potential for value-addition are small and demand for biomass is still low. One of the industrialists explains that the key is to stop looking at seaweed just as a source of single components (carrageenan, alginates, etc.). Another explains that associations should be made between industries in order to enhance the co-products of extraction or processing of each other. Among recent technological developments, the bio-refinery concept seems to be highly suitable model for optimized macroalgae exploitation. This concept can be considered to be an integral unit that can accept various biological nonfood feedstocks and convert them into a range of useful products including chemicals, energy, and materials (Celiktas et al, 2017.) Yet, only one interviewee mentioned their company having one.

Association between seaweed molecules and other active molecules

"The real issue, *in-fine* and we are already there: is to associate active extracts or molecules of interest of algae with other active extracts or molecules of interest of other plants," French scientist expert in seaweed.

Although this issue was raised by only one actor, it still seemed important to talk about it. The actor in question is a scientist with more than 20 years of experience in the field of algae. He explains that new products are currently the source of much research: coupling a molecule of interest from algae with another biological molecule, which cannot be reproduced by synthetic chemistry. This coupling could have very promising effects in the preventive treatment of certain very widespread diseases such as cancer, but also serve as a barrier to the virus, by conferring a superior power of resistance and self-destruction to our cells. This breakthrough would open doors to major innovations for the pharmaceutical industry and others.

Improve legislation

"The biggest issue for Europe at the moment is the legislation," European industrialist working in all sectors of industry with seaweed.

Five of the interviewees mentioned legislation on use of ingredients as a major obstacle to the development of the sector. As the market for seaweed develops in western countries, it generates novel legal considerations. This section gives an insight into some of the legislation impeding or favoring market development in the European Union and United States.

Human consumption as food and additive

In the European Union, specifications for food additives based on seaweed are laid down in the annexes to Commission Regulation (EU) No 231/2012. For whole seaweed, there are 29 species of seaweeds (brown, red and green) that are accepted as food in Europe as not novel. A novel food is any food or ingredient that does not have a significant history of consumption in the EU prior to 15 May 1997 (European Commission, 1997). The decision of placing a new species as food on the market depends of its inclusion on this list, a potentially lengthy and expensive process with no guarantee of success. However, to enter the European market, seaweed and seaweed extracts must also be compliant with the General Food Law of the European Union due to the heavy metals, chemicals and other pollutants they accumulate (Barbier *et al.*, 2019).

The United States Food & Drug Administration (FDA) currently has several regulations controlling the consumption of seaweed and kelp products. The FDA considers kelp “generally recognized as safe” (GRAS), but only when used in other foods as an additive. The FDA also has specific regulations for both brown and red algae. These regulations list the names of applicable GRAS species, and note both brown and red algae’s functional uses include “flavor enhancer” and “flavor adjuvant.” Listed brown and red algae species may be considered GRAS, whether or not they are meant to impart any of their own taste to the food to which they are added. However, GRAS determinations do not apply to singular products such as kelp or seaweed in its whole raw, cooked, or dried forms. In the United States neither the FDA nor the U.S. Department of Agriculture (USDA) has regulated the sale of seaweed in its whole form. Without federal guidance on the food safety risks of seaweed in its whole form, states are unsure how to proceed with their own laws and regulations, impeding the growth of the industry (Janasie, 2018).

Pharmaceutical

A new medicine or drug will take on average at least 10 years from initial discovery to the marketplace, with clinical trials alone taking six to seven years on average. After determining that the results of the clinical trials indicate the compound is both safe and effective, the sponsoring company submits a new drug application (NDA) or biologics license application (BLA) to the FDA requesting approval to market the drug. These applications contain the results and data analysis from the entire clinical development program, as well as the earlier preclinical testing and proposals for manufacturing and labelling of the new medicine. (PHRMA, 2015).

Plant Bio-Stimulant

The European Union is becoming the first legislative organization to recognize plant bio-stimulants (PBS) as a separate group of agricultural inputs. This regulation of PBS within the EU will bring new insights to the expansion of seaweed extracts in the recent future (Boukhari *et al.*, 2020).

However, it is not the case in the United States. In the absence of a clear definition in current regulations, PBS is often defined by method of exclusion, so it is neither a pesticide nor a fertilizer or a plant growth regulator (PGR). However, this method often leads to confusion because it is hard to distinguish between PBS and PGR, as these two types of products have partial overlapping. Algae extract is considered a PGR and is regulated under the FIFRA Act by the EPA. The registration requirements for algae extract are similar to those for pesticides. The EPA’s definition of a PBS is based on the product's mechanism of action, which is still a topic of discussion (Xiahoa, 2019).

Cosmetics

Seaweed used as a plant extract is not restricted for cosmetic use (Bedoux *et al.*, 2014) under strict rules concerning the use of chemical substances (EU regulation No. 1223/2009 on cosmetic products) but still must satisfy consumer demand for products containing effective natural and nontoxic ingredients. .

In the United States, except for color additives and those ingredients that are prohibited or restricted by regulation, a manufacturer may use any ingredient in the formulation of a cosmetic, provided that the ingredient and the finished cosmetic are safe under labeled or customary conditions of use, the product is properly labeled, and the use of the ingredient does not otherwise cause the cosmetic to be adulterated or misbranded under the laws that FDA enforces.

Regulation of Conventional Alternatives to Seaweed

Fossil fuels, plastics, petrochemicals and insecticides have well-documented and generally negative impacts on global ecosystems. Seaweed could replace many of these products. As of now the biggest obstacle for a transition to seaweed is the price of petroleum and natural gas. Regulations aiming to reduce our impact on the global environment may be key in the evolution of seaweed markets. Bans of plastic products and other environmentally harmful products are already encouraging alternatives. According to a U.N. report, 127 countries had implemented some type of policy regulating plastic bags by July 2018 (UNEP, 2018). Other initiatives like the ban of single-use plastic in France promotes the use of bioplastic from sustainable sources.

There is a gradual trend against fossil fuels around the world. More than 14 countries and more than 20 cities around the world have proposed banning the sale of fossil fuel-powered vehicles. Europe is to develop a strategy to eliminate petrol and diesel cars by 2030 (*2030 : la fin des voitures dans les centres-villes*, 2020)**.** Algae-based fuel is an interesting biofuel alternative because it does not compete with food crops for arable land, utilizes no drinking water and possibly achieves higher productivity. Another advantage is that it is processed into butanol which is more calorific than regular ethanol.

Europe adopted new rules on fertilizers in May 2019 in order to turn to more environmentally friendly agriculture (Conseil européen, 2019)**.** In Florida, 90 communities have decided to ban fertilizers containing phosphorus and nitrogen (Pinkard, 2019). Bans on pesticides are also going into effect, especially in Europe (PAN UK, 2018)**.** In India, the Ministry of Agriculture issued a draft ordinance on 14 May 2020 prohibiting the manufacture and sale of 27 pesticides "likely to pose risks to humans and animals" (Sayanta, 2020)**.** There is a global transition in agriculture towards less harmful practices and PBS come as the natural solution.

While legislation is currently an impediment on some industries, it can also be seen that it is an important lever to be raised to trigger the development of certain sectors. Several companies are coming together, especially in Europe, to work together on legislative proposals that allow them to develop their activities like the European Algae Biomass Association (EABA).

V. Discussion

Forecasts indicate a positive trend for growth of seaweed utilization in **cosmetic** products as it is a natural product with moisturizing and antioxidant properties greatly used in skin and hair product. However, this sector is structured around the marketing and storytelling around the products rather than their bioactivity. Due to its high value-added, cosmetic companies do not need large volumes. Small and medium size companies providing high quality wild harvested seaweed are the prime candidate as supplier. Interviews have highlighted that the demand for seaweed as an active ingredient in cosmetics is too low to justify industrial production and does not match in terms of consumer perception of the product. In the same sense, despite great medical value and potential for innovation, because of its financial and time-consuming constraints, seaweed for the **pharmaceutical** sector is a market developing very slowly with a need of scientific breakthroughs.

The market for direct consumption in Asia should stay strong, but, although developing, in occidental countries it will take time to emerge and support industrial production. For such countries, if the **food** sector is to absorb a scaling up of production, it will be through indirect consumption in food formulations. Indeed, interviews and literature seem to agree that it is as texturing agents for novel foods, such as non-meat products, or as health supplements or **nutraceuticals** that this market segment is the more likely to expand.

Market segments that have shown most the promise are in agriculture. Indeed, market segments that have shown all together probative results in term of utilization, a strong and existing demand, and a potential for large volume absorption with creation of value-added are the **PBS** and **feed** sectors. Feeding a growing world population while public interest strongly supports sustainable and ecological alternatives to conventional agri-inputs, feed and veterinary medicine, is a challenge that pushes towards the use of bio-solutions from seaweed.

As the seaweed sector and its various applications are still young, we can see that the challenges to be met for its development are still numerous. In terms of production there is a need for more biological knowledge of species and cultivation techniques to insure biomass availability, homogeneity and cost-effectiveness. Processing needs to be optimized to maximize value obtained from the whole seaweed, through novel process techniques and the utilizations of all or most components. Lastly, legislation needs to be adapted to this industry and its specificities. These challenges present the various keys to the development of this new industry and must be thought in the current ecological and humanitarian context.

VI. Recommendations

While the study provides an overview of the demand for seaweed components, the various sectors and their trends, a more structured market model would provide a more relevant economic vision. Indeed, precise volumes and added value of current and emerging markets, through the constituents of interest, represent a more solid basis for the choice of future investments.

An upstream intra-sector analysis by group or cluster of seaweed professionals would be judicious before cross-referencing between categories. Indeed, some actors of the same environment bring out contradictory ideas that it seems relevant to analyze in parallel. However, the number of actors interviewed in each sector must be higher to confer scientific validity to the intra-sector analysis.

In addition, with larger samples, a Multiple Correspondence Analysis (MCA) can be performed. Allowing to study the association in several qualitative variables, it would be a better understanding of the trends, especially by considering the objectivity and variability of the actors. MCA would also be useful in the representation of maps on which the proximity of stakeholders is visually observable.

Moreover, a characterization of the actors (producers, industrialists, and researchers) on the international scene would allow a perception of the seaweed sector as a whole, provided that the following issues are addressed:

- To deepen the study by interviewing industrialists who do not use seaweed but would be likely to use them. Taking these actors into account in the study could indeed bring a better characterization of the future demand.
- The way in which industries are represented (VSE, SME, multinational, etc.) as well as their main locations on the globe and the reasons that motivate these choices. The percentages of markets held as well as the evolutions of these percentages must be derived.
- The interrelationships between the actors of the sector: the stakes of the exchanges, with a more developed geopolitical and geo-economic vision of the markets.

Some constituents present important prospects, it seems then necessary to identify the technical constraints in the treatment of constituents in industrial processes, in particular separation, concentration and chemical fragmentation and restructuring. At the same time, it would be advisable to take stock of the progress made in overcoming these constraints.

Finally, reducing the scope of the study into multiple studies according to specific objectives would allow a thorough socio-economic analysis of the real stakes in the algae sector. The risk of macroscopic analysis is the over-simplification of interactions between entities and flux. Mapping out the global seaweed industry with its complexity becomes necessary in order to illustrate best the on-field realities.

References

2030 : la fin des voitures dans les centres-villes (2020) *Hesion - Smart Parking Solutions*. Available at: https://hesion-park.com/en/uncategorized/2030-la-fin-des-voitures-dans-les-centres-villes/ (Accessed: 13 September 2020).

AACC, (American Association of Cereal Chemists) (2001) 'The Definition of Dietary Fiber', *Report of the Dietary Fiber Definition Committee to the Board of Directors of the American Association Of Cereal Chemists*.

Abu-Ghannam, N. and Cox, S. (2013) 'Seaweed-based Functional Foods', in Hernández-Ledesma, B. and Herrero, M. (eds) *Bioactive Compounds from Marine Foods*. Chichester, UK: John Wiley & Sons Ltd, pp. 313–327. doi: 10.1002/9781118412893.ch14.

Agasse, A. *et al.* (2015) *Polysaccharides Marins pour les Santés Végétale, Animale et Humaine*, *ResearchGate*. Available at: https://www.researchgate.net/publication/279525877_Polysaccharides_Marins_pour_les_Santes_Vegetale_Animale_et_Humaine (Accessed: 9 September 2020).

Alba, K. and Kontogiorgos, V. (2019) 'Seaweed Polysaccharides (Agar, Alginate Carrageenan)', in *Encyclopedia of Food Chemistry*. Elsevier, pp. 240–250. doi: 10.1016/B978-0-08-100596-5.21587-4.

Ali Ahmed, A. B. *et al.* (2017) 'Seaweed Polysaccharides and Their Production and Applications', in *Seaweed Polysaccharides*. Elsevier, pp. 369–382. doi: 10.1016/B978-0-12-809816-5.00020-7.

Allied Market Research (2019) *5 Major Aquaculture Market Size and Demand | Industry Forecast, 2025*, *Allied Market Research*. Available at: https://www.alliedmarketresearch.com/5-major-aquaculture-market (Accessed: 10 September 2020).

Alves, A., Sousa, R. A. and Reis, R. L. (2013) 'A practical perspective on ulvan extracted from green algae', *Journal of Applied Phycology*, 25(2), pp. 407–424. doi: 10.1007/s10811-012-9875-4.

Anses (2017) *Que sont les vitamines ? | Anses - Agence nationale de sécurité sanitaire de l'alimentation, de l'environnement et du travail*. Available at: https://www.anses.fr/fr/content/que-sont-les-vitamines (Accessed: 4 September 2020).

Armisén, R. and Gaiatas, F. (2009) 'Agar', in *Handbook of Hydrocolloids*. Elsevier, pp. 82–107. doi: 10.1533/9781845695873.82.

Aryee, A. N., Agyei, D. and Akanbi, T. O. (2018) 'Recovery and utilization of seaweed pigments in food processing', *Current Opinion in Food Science*, 19, pp. 113–119. doi: 10.1016/j.cofs.2018.03.013.

Ashwell, M. (2002) *Concepts of functional foods*. Brussels: International Life Sciences Institute (ILSI) Europe.

Barbier, M. *et al.* (2019) *PEGASUS - Phycomorph European Guidelines for a Sustainable Aquaculture of Seaweeds*. Phycomorph. Available at: https://www.phycomorph.org/pegasus-phycomorph-european-guidelines-for-a-sustainable-aquaculture-of-seaweeds.

Bedoux, G. *et al.* (2014) 'Bioactive Components from Seaweeds: Cosmetic Applications and Future Development', in *Advances in Botanical Research*. Elsevier, pp. 345–378. doi: 10.1016/B978-0-12-408062-1.00012-3.

biogasman (2019) 'The Application of Biogas - A List of the 7 Top Uses', *Anaerobic Digestion Community Website*, 24 February. Available at: https://anaerobic-digestion.com/application-of-biogas/ (Accessed: 13 September 2020).

Boukhari, M. E. M. E. *et al.* (2020) 'Trends in Seaweed Extract Based Biostimulants: Manufacturing Process and Beneficial Effect on

Soil-Plant Systems’, *Plants*, 9(3), p. 359. doi: 10.3390/plants9030359.

Boulho, R. (2017) *Application de procédés éco-responsables pour l’extraction de molécules de la macroalgue Solieria chordalis, caractérisations chimiques et étude d’activités biologiques*. These de doctorat. Lorient. Available at: https://www.theses.fr/2017LORIS465 (Accessed: 5 September 2020).

Burlot, A.-S. (2016) *Valorisation des métabolites d’algues proliférantes par voie enzymatique : applications dans les domaines de la nutrition et santé animale, végétale et humaine, de la cosmétique et de l’environnement*. phdthesis. Université de Bretagne Sud. Available at: https://tel.archives-ouvertes.fr/tel-01511879 (Accessed: 11 September 2020).

Burtin, P. (2003) ‘Nutritional value of seaweeds’, *Electronic Journal of Environmental, Agricultural and Food Chemistry*, 2(4), pp. 498–503.

CEVA (2011) ‘La biodiversité algale au service du développement économique de Mayotte’, Tome 1, p. 125.

Cho, T. J. and Rhee, M. S. (2019) ‘Health Functionality and Quality Control of Laver (Porphyra, Pyropia): Current Issues and Future Perspectives as an Edible Seaweed’, *Marine Drugs*, 18(1), p. 14. doi: 10.3390/md18010014.

Conseil européen (2019) *L’UE adopte de nouvelles règles sur les engrais*.

Cornish, M. L. and Garbary, D. J. (2010) ‘Antioxidants from macroalgae: potential applications in human health and nutrition’, *ALGAE*, 25(4), pp. 155–171. doi: 10.4490/algae.2010.25.4.155.

Cotas, J. *et al.* (2020) ‘A Comprehensive Review of the Nutraceutical and Therapeutic Applications of Red Seaweeds (Rhodophyta)’, *Life*, 10(3), p. 19. doi: 10.3390/life10030019.

Dahms, H. and Dobretsov, S. (2017) ‘Antifouling Compounds from Marine Macroalgae’, *Marine Drugs*, 15(9), p. 265. doi: 10.3390/md15090265.

Déléris, P., Nazih, H. and Bard, J.-M. (2016) ‘Seaweeds in Human Health’, in *Seaweed in Health and Disease Prevention*. Elsevier, pp. 319–367. doi: 10.1016/B978-0-12-802772-1.00010-5.

Delgado-Vargas, F., Jiménez, A. R. and Paredes-López, O. (2000) ‘Natural Pigments: Carotenoids, Anthocyanins, and Betalains — Characteristics, Biosynthesis, Processing, and Stability’, *Critical Reviews in Food Science and Nutrition*, 40(3), pp. 173–289. doi: 10.1080/10408690091189257.

Draget, K. I. (2009) ‘Alginates’, in *Handbook of Hydrocolloids*. Elsevier, pp. 807–828. doi: 10.1533/9781845695873.807.

Dumay, J. and Morançais, M. (2016) ‘Proteins and Pigments’, in *Seaweed in Health and Disease Prevention*. Elsevier, pp. 275–318. doi: 10.1016/B978-0-12-802772-1.00009-9.

Eleftherios Bonos (2017) ‘The Seaweed Ascophyllum nodosum as a Potential Functional Ingredient in Chicken Nutrition’. doi: 10.4172/2572-3103.1000140.

Elia, J. (2019) *Fractionnement bioguidé de Laurencia papillosa de la côte libanaise : identification du cholest-4-èn-3-one, un nouvel agoniste de LXR cytotoxique pour les cellules du cancer du sein*. These de doctorat. Nantes. Available at: https://www.theses.fr/2019NANT4008 (Accessed: 5 September 2020).

Emerging Markets Online (2020) *Algae Market Study- Algae 2020: Biofuels Markets and Commercialization Outlook - Algae Companies - Algae 2020, Vol 3: Emerging Markets for Feed, Fuels, Nutrition, Omega 3s & Astaxanthin*. Available at: http://www.emerging-markets.com/algae/ (Accessed: 11 September 2020).

Erlania and Nyoman Radiarta (2015) ‘The Use of Seaweeds Aquaculture for Carbon Sequestration: A Strategy for Climate Change Mitigation’, *Journal of Geodesy and Geomatics Engineering*, 2(2). doi: 10.17265/2332-8223/2015.06.006.

European Commission (1997) *Novel food*, *Food Safety - European Commission*. Available at: https://ec.europa.eu/food/safety/novel_food_en (Accessed: 13 September 2020).

Evans, D. *et al.* (2017) *Student Perceptions About Benefits From an Extracurricular Curriculum: A Qualitative Study of the Underserved Pathway*, *PRiMER*. STFM. doi: 10.22454/PRiMER.2017.153424.

Evans, F. D. and Critchley, A. T. (2014) ‘Seaweeds for animal production use’, *Journal of Applied Phycology*, 26(2), pp. 891–899. doi: 10.1007/s10811-013-0162-9.

FAO (1990) ‘Chapter III: Properties, manufacture and application of seaweed polysaccharides - agar, carrageenan and algin’, in *Training Manual on Gracilaria Culture and Seaweed Processing in China*. Available at: http://www.fao.org/3/AB730E/AB730E03.htm (Accessed: 5 September 2020).

FAO (2014) *La situation mondiale des pêches et de l’aquaculture*. Rome, Italy: Organisation des Nations Unies pour l’alimentation et l’agriculture. Available at: http://fao.org/2/sofia14f.

FAO (2016) *FAOSTAT*. Available at: http://www.fao.org/faostat/en/#data/RL/visualize.

FAO (2018) *The global status of seaweed production, trade and utilization*. 124. Rome, Italy: FAO, p. 1.

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

Featherstone, S. (2015) ‘Ingredients used in the preparation of canned foods’, in *A Complete Course in Canning and Related Processes*. Elsevier, pp. 147–211. doi: 10.1016/B978-0-85709-678-4.00008-7.

Fijan, R., Šostar-Turk, S. and Lapasin, R. (2007) ‘Rheological study of interactions between non-ionic surfactants and polysaccharide thickeners used in textile printing’, *Carbohydrate Polymers*, 68(4), pp. 708–717. doi: 10.1016/j.carbpol.2006.08.006.

Fleurence, J., Levine, I. and Stefan, K. (2016) *Seaweed in health and disease prevention*. Academic Press.

Ford, L. *et al.* (2020) ‘Polyphenols from Brown Seaweeds as a Potential Antimicrobial Agent in Animal Feeds’, *ACS Omega*, 5(16), pp. 9093–9103. doi: 10.1021/acsomega.9b03687.

Fortier, J.-F. and Florentin, A. (2020) *Phycobiliprotéine: définition et explications*, *AquaPortail*. Available at: https://www.aquaportail.com/definition-1315-phycobiliproteine.html (Accessed: 5 September 2020).

Fortune business insights (2019) *Biostimulants Market Size, Share, Growth | Global Report [2020-2027]*. Available at: https://www.fortunebusinessinsights.com/industry-reports/biostimulants-market-100414 (Accessed: 13 September 2020).

Freile-Pelegrin, Y. and Daniel, R. (2014) ‘Bioactive Phenolic Compounds from Algae’.

Future Market Insights (2018) *Bioplastics for Packaging Market: Global Industry Analysis, Size and Forecast, 2017 to 2027*. Available at: https://www.futuremarketinsights.com/reports/bioplastics-packaging-market (Accessed: 12 September 2020).

Future Market Insights (2019) ‘End Usage of Macroalgae in Food Sector to Stay Dominant in the Global Macroalgae Market’. Available at: https://www.fmiblog.com/end-usage-of-macroalgae-in-food-sector-to-stay-dominant-in-the-global-macroalgae-market/ (Accessed: 10 September 2020).

Ge, B. *et al.* (2006) 'Antioxidant properties of recombinant allophycocyanin expressed in Escherichia coli', *Journal of Photochemistry and Photobiology B: Biology*, 84(3), pp. 175–180. doi: 10.1016/j.jphotobiol.2006.02.008.

Gomez-Zavaglia, A. *et al.* (2017) 'The Potential of Seaweeds as a Source of Functional Ingredients of Prebiotic and Antioxidant Value', *MDPI*. Available at: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6770939/.

Gomez-Zavaglia, A. *et al.* (2019) 'The Potential of Seaweeds as a Source of Functional Ingredients of Prebiotic and Antioxidant Value', *Antioxidants*, 8(9), p. 406. doi: 10.3390/antiox8090406.

Grand View Research (2017) *Algae Biofuel Market Size, Share | Global Industry Analysis Report, 2025*. Available at: https://www.grandviewresearch.com/industry-analysis/algae-biofuel-market (Accessed: 13 September 2020).

Grand View Research (2018) *Biostimulants Market Size, Share & Trends | Industry Report, 2018-2025*. Available at: https://www.grandviewresearch.com/industry-analysis/biostimulants-market?fbclid=IwAR08sqjcb7dUz60Tx9N4ML03sm13GSZyZTskOfQEh31OJuCyerHkI3nJC94 (Accessed: 10 September 2020).

Grand View Research (2020) *Global Nutraceutical Market Growth Analysis Report, 2020-2027*. Available at: https://www.grandviewresearch.com/industry-analysis/nutraceuticals-market (Accessed: 6 September 2020).

Holdt, S. L. and Kraan, S. (2011) 'Bioactive compounds in seaweed: functional food applications and legislation', *Journal of Applied Phycology*, 23(3), pp. 543–597. doi: 10.1007/s10811-010-9632-5.

Hughes, A. D. *et al.* (2012) 'Biogas from Macroalgae: is it time to revisit the idea?', *Biotechnology for Biofuels*, 5(1), p. 86. doi: 10.1186/1754-6834-5-86.

Illera-Vives, M. *et al.* (2020) 'Agricultural uses of seaweed', in *Sustainable Seaweed Technologies*. Elsevier, pp. 591–612. doi: 10.1016/B978-0-12-817943-7.00020-2.

Imeson, A. P. (2009) 'Carrageenan and furcellaran', in *Handbook of Hydrocolloids*. Elsevier, pp. 164–185. doi: 10.1533/9781845695873.164.

IMR international (2019) 'Food Hydrocolloid Market-2018 estimates for 2019 conference'. Lisbon, Portugal. Available at: www.hydrocolloid.com.

Ito, K. and Hori, K. (1989) 'Seaweed: Chemical composition and potential food uses', *Food Reviews International*, 5(1), pp. 101–144. doi: 10.1080/87559128909540845.

Janarthanan, M. and Senthil Kumar, M. (2018) 'The properties of bioactive substances obtained from seaweeds and their applications in textile industries', *Journal of Industrial Textiles*, 48(1), pp. 361–401. doi: 10.1177/1528083717692596.

Janasie, C. (2018) 'Seaweed, Kelp, and Other Aquaculture Products – Legal Issues with Cultivation and Production as Food Sources'. AALA. Available at: https://www.aglaw-assn.org/wp-content/uploads/7D-Seaweed-Kelp-_-Other-Aquaculture-Products-AALA-2018-Janasie.pdf.

du Jardin, P. (2015) 'Plant biostimulants: Definition, concept, main categories and regulation', *Scientia Horticulturae*, 196, pp. 3–14. doi: 10.1016/j.scienta.2015.09.021.

Kadam, S. U. and Prabhasankar, P. (2010) 'Marine foods as functional ingredients in bakery and pasta products', *Food Research International*, 43(8), pp. 1975–1980. doi: 10.1016/j.foodres.2010.06.007.

Kadam, S. U., Tiwari, B. K. and O'Donnell, C. P. (2015) 'Extraction, structure and biofunctional activities of laminarin from brown algae', *International Journal of Food Science & Technology*, 50(1), pp. 24–31. doi: 10.1111/ijfs.12692.

Kaliaperumal, N. (2003) ‘Products from seaweeds’, *SDMRI Research Publication*, 3, pp. 33–42.

Kalra, E. K. (2003) ‘Nutraceutical-definition and introduction’, *AAPS PharmSci*, 5(3), pp. 27–28. doi: 10.1208/ps050325.

Kenicer, G., Bridgewater, S. and Milliken, W. (2000) ‘The Ebb and Flow of Scottish Seaweed Use’, *Botanical Journal of Scotland*, 52(2), pp. 119–148. doi: 10.1080/13594860009441750.

Kidgell, J. T. *et al.* (2019) ‘Ulvan: A systematic review of extraction, composition and function’, *Algal Research*, 39, p. 101422. doi: 10.1016/j.algal.2019.101422.

Kim, S.-K. (2011) *Marine Medicinal Foods: Implications and Applications, Macro and Microalgae*. Korea: Academic Press (Food and Nutrition Rechearch).

Kim, S.-K. and Wijesekara, I. (2011) ‘Chapter 18 - Anticoagulant Effect of Marine Algae’, in Kim, S.-K. (ed.) *Advances in Food and Nutrition Research*. Academic Press (Marine Medicinal Foods), pp. 235–244. doi: 10.1016/B978-0-12-387669-0.00018-1.

Kinley, R. D. *et al.* (2020) ‘Mitigating the carbon footprint and improving productivity of ruminant livestock agriculture using a red seaweed’, *Journal of Cleaner Production*, 259, p. 120836. doi: 10.1016/j.jclepro.2020.120836.

Kraan, S. (2012) ‘Algal Polysaccharides, Novel Applications and Outlook’, *Carbohydrates - Comprehensive Studies on Glycobiology and Glycotechnology*. doi: 10.5772/51572.

Kraan, S. (2016) ‘Chapter 6 - Seaweed and Alcohol: Biofuel or Booze?’, in Fleurence, J. and Levine, I. (eds) *Seaweed in Health and Disease Prevention*. San Diego: Academic Press, pp. 169–184. doi: 10.1016/B978-0-12-802772-1.00006-3.

Lakhdar, F. (2018) *Contribution à l’étude des potentialités antiproliférative et antibactérienne des algues brunes et rouges de la côte d’El Jadida pour une valorisation médicale et environnementale*. These de doctorat. Nantes. Available at: https://www.theses.fr/2018NANT4037 (Accessed: 5 September 2020).

Lamm, B. (2019) ‘Algae might be a secret weapon to combatting climate change’, 1 October.

Le Bras, Q. *et al.* (2014) *Etude de la consommation des algues alimentaires en France*. Etude nationale 35. Les publications du Pôle halieutique AGROCAMPUS OUEST, p. 72.

Li, B. *et al.* (2008) ‘Fucoidan: Structure and Bioactivity’, *Molecules*, 13(8), pp. 1671–1695. doi: 10.3390/molecules13081671.

Lim, S. J. and Wan Aida, W. M. (2017) ‘Chapter 3 - Extraction of Sulfated Polysaccharides (Fucoidan) From Brown Seaweed’, in Venkatesan, J., Anil, S., and Kim, S.-K. (eds) *Seaweed Polysaccharides*. Elsevier, pp. 27–46. doi: 10.1016/B978-0-12-809816-5.00003-7.

Linden (2014) *Dutch seaweed : an economic analysis of Dutch seaweed (proteins) in the food and feed industry | Online MSc theses successfully defended at Wageningen University*. Available at: https://library.wur.nl/WebQuery/theses/2070974 (Accessed: 6 September 2020).

Loureiro, R., Gachon, C. M. M. and Rebours, C. (2015) ‘Seaweed cultivation: potential and challenges of crop domestication at an unprecedented pace’, *New Phytologist*, 206(2), pp. 489–492. doi: 10.1111/nph.13278.

MacArtain, P. *et al.* (2007) ‘Nutritional Value of Edible Seaweeds’, in *Nutrition Reviews*. International Life Sciences Institute, pp. 535–543.

Magnan, S. *et al.* (2018) ‘Efficacy of a Carrageenan gel Against Transmission of Cervical HPV (CATCH): interim analysis of a randomized, double-blind, placebo-controlled, phase 2B trial', *Clinical Microbiology and Infection*. Available at: https://www.clinicalmicrobiologyandinfection.com/action/showPdf?pii=S1198-743X%2818%2930350-1.

Maia, M. R. G. *et al.* (2016) 'The Potential Role of Seaweeds in the Natural Manipulation of Rumen Fermentation and Methane Production', *Scientific Reports*, 6(1), p. 32321. doi: 10.1038/srep32321.

Makkar, H. P. S. *et al.* (2016) 'Seaweeds for livestock diets: A review', *Animal Feed Science and Technology*, 212, pp. 1–17. doi: 10.1016/j.anifeedsci.2015.09.018.

Markets and markets (2019) *Feed Additives Market Share | Global Industry Report - 2023*. Available at: https://www.marketsandmarkets.com/Market-Reports/feed-additives-market-870.html (Accessed: 10 September 2020).

McHugh, D. J. (2003) *A guide to the seaweed industry*. Rome: Food and Agriculture Organization of the United Nations (FAO fisheries technical paper, 441).

North Sea Farm Foundation (2018) 'Identification of the seaweed biostimulant market (phase 2)'. *Bio4safe WP1 Market analyses*, July.

O'Connor, D. (2011) 'Algae as a feedstock for biofuels. An assessment of the current status and potential for algal biofuels production', *IEA Bioenergy's Summary Report*, Task 39, p. 25.

Oiso, T. (1975) 'Incidence of Stomach Cancer and Its Relation to Dietary Habits and Nutrition in Japan between 1900 and 1975', *Cancer research*, 35(11 Part 2), pp. 3254–3258.

Olatunji, O. (2020) *Aquatic Biopolymers - Understanding their Industrial Significance and Environmental Implications*. Edited by O. Olatunji. Cham: Springer International Publishing (Springer Series on Polymer and Composite Materials). doi: 10.1007/978-3-030-34709-3_6.

Omar, H., Al-Judaibi, A. and El-Gendy, A. (2018) 'Antimicrobial, Antioxidant, Anticancer Activity and Phytochemical Analysis of the Red Alga, Laurencia papillosa', *International Journal of Pharmacology*, 14(4), pp. 572–583. doi: 10.3923/ijp.2018.572.583.

Padam, B. S. and Chye, F. Y. (2020) 'Seaweed components, properties, and applications', in *Sustainable Seaweed Technologies*. Elsevier, pp. 33–87. doi: 10.1016/B978-0-12-817943-7.00002-0.

Padmakumar, K. and Ayyakkannu, K. (1997) 'Seasonal Variation of Antibacterial and Antifungal Activities of the Extracts of Marine Algae from Southern Coasts of India', *Botanica Marina*, 40(1–6). doi: 10.1515/botm.1997.40.1-6.507.

PAN UK (2018) 'Which Pesticides are Banned in Europe?'

Pangestuti, R. and Kim, S.-K. (2011) 'Biological activities and health benefit effects of natural pigments derived from marine algae', *Journal of Functional Foods*, 3(4), pp. 255–266. doi: 10.1016/j.jff.2011.07.001.

Pangestuti, R. and Kim, S.-K. (2015) 'An Overview of Phycocolloids: The Principal Commercial Seaweed Extracts', in *Marine Algae Extracts: Processes, Products, and Applications*. Weinheim, Germany, pp. 319–330. doi: 10.1002/9783527679577.ch19.

Peng, Y. *et al.* (2015) 'Chemical composition of seaweeds', in *Seaweed Sustainability*. Elsevier, pp. 79–124. doi: 10.1016/B978-0-12-418697-2.00005-2.

Pérez, M., Falqué, E. and Domínguez, H. (2016) 'Antimicrobial Action of Compounds from Marine Seaweed', *Marine Drugs*, 14(3), p. 52. doi: 10.3390/md14030052.

Person, J. (2011) *Livre Turquoise : Algues, filières du futur*. Editions Adebiotech.

PHRMA (2015) 'Biopharmaceutical Research & Development: The Process Behind New Medicines'.

Pinkard, C. (2019) *Summer Fertilizer Ban Seeks To Protect Florida Waterways*, *WUSF Public Media*. Available at: https://wusfnews.wusf.usf.edu/environment/2019-05-30/summer-fertilizer-ban-seeks-to-protect-florida-waterways (Accessed: 13 September 2020).

Plaza, M., Cifuentes, A. and Ibáñez, E. (2008) 'In the search of new functional food ingredients from algae', *Trends in Food Science & Technology*, 19(1), pp. 31–39. doi: 10.1016/j.tifs.2007.07.012.

Rajapakse, N. and Kim, S.-K. (2011) 'Nutritional and Digestive Health Benefits of Seaweed', in *Advances in Food and Nutrition Research*, pp. 17–28.

Rajendran, N. *et al.* (2012) 'Seaweeds can be a new source for bioplastics', *Journal of Pharmacy Research*, 5(3), pp. 1476–1479.

Ross, C. B. (2017) *Focus on Fibres: Sustainable Seaweed Fabric... SeaCell™*, *The Sustainable Fashion Collective*. Available at: https://www.the-sustainable-fashion-collective.com/2017/05/11/new-sustainable-seaweed-fabric-seacell (Accessed: 13 September 2020).

Roy, S. and Rhim, J.-W. (2019) 'Agar-based antioxidant composite films incorporated with melanin nanoparticles', *Food Hydrocolloids*, 94, pp. 391–398. doi: 10.1016/j.foodhyd.2019.03.038.

Rupérez, P. (2002) 'Mineral content of edible marine seaweeds', *Food Chemistry*, 79(1), pp. 23–26. doi: 10.1016/S0308-8146(02)00171-1.

Saraswati *et al.* (2019) 'Sargassum Seaweed as a Source of Anti-Inflammatory Substances and the Potential Insight of the Tropical Species: A Review', *Marine Drugs*, 17(10), p. 590. doi: 10.3390/md17100590.

Sayanta, B. (2020) 'Agriculture ministry proposal to ban 27 pesticides faces resistance', 26 June.

Sen, S. and Chakraborty, R. (2011) 'The Role of Antioxidants in Human Health', in *Oxidative Stress: Diagnostics, Prevention, and Therapy*. Washington, DC: American Chemical Society (ACS Symposium Series), pp. 1–37. doi: 10.1021/bk-2011-1083.ch001.

Shahbandeh, M. (2020) *Cosmetics Industry - Statistics & Facts*, *Statista*. Available at: https://www.statista.com/topics/3137/cosmetics-industry/ (Accessed: 5 September 2020).

Smit, A. J. (2004) 'Medicinal and pharmaceutical uses of seaweed natural products: A review', *Journal of Applied Phycology*, 16(4), pp. 245–262. doi: 10.1023/B:JAPH.0000047783.36600.ef.

Suleria, H. A. R. *et al.* (2015) 'Marine-Based Nutraceuticals: An Innovative Trend in the Food and Supplement Industries', *Marine Drugs*, 13(10), pp. 6336–6351. doi: 10.3390/md13106336.

Tapera, O. *et al.* (2019) 'Determinants of access and utilization of cervical cancer treatment and palliative care services in Harare, Zimbabwe', *BMC Public Health*, 19(1), p. 1018. doi: 10.1186/s12889-019-7355-3.

Tiwari, B. K. and Troy, D. J. (2015) 'Seaweed sustainability – food and nonfood applications', in *Seaweed Sustainability*. Elsevier, pp. 1–6. doi: 10.1016/B978-0-12-418697-2.00001-5.

UNEP (2018) *SINGLE-USE PLASTICS A Roadmap for Sustainability*.

Van Ginneken, V. J. *et al.* (2011) 'Polyunsaturated fatty acids in various macroalgal species from north Atlantic and tropical seas', *Lipids in Health and Disease*, 10, p. 104. doi: 10.1186/1476-511X-10-104.

Van Iersel, S. *et al.* (2009) 'Algae-based biofuels: a review of challenges and opportunities for developing countries.', *Italy: Food and* *agriculture Organization of the Unites Nations*, p. 60.

Venkatesan, J., Anil, S. and Kim, S.-K. (2017) 'Chapter 1 - Introduction to Seaweed Polysaccharides', in Venkatesan, J., Anil, S., and Kim, S.-K. (eds) *Seaweed Polysaccharides*. Elsevier, pp. 1–9. doi: 10.1016/B978-0-12-809816-5.00001-3.

Venugopal, V. (2019) 'Sulfated and Non-Sulfated Polysaccharides from Seaweeds and their Uses: An Overview', p. 16.

Vinoj Kumar, V. and Kaladharan, P. (2007) 'Amino acids in the seaweeds as an alternate source of protein for animal feed', *Journal of the Marine Biological Association of India*, 49(1), pp. 35–40.

WALSEA (2020) 'Les macroalgues marines : Applications actuelles & perspectives de valorisation'.

Wijesekara, I., Pangestuti, R. and Kim, S.-K. (2011) 'Biological activities and potential health benefits of sulfated polysaccharides derived from marine algae', *Carbohydrate Polymers*, 84(1), pp. 14–21. doi: 10.1016/j.carbpol.2010.10.062.

World Bank Group (2016) 'Seaweed Aquaculture for Food Security, Income Generation and Environmental Health in Tropical Developing Countries'. World Bank. Available at: https://openknowledge.worldbank.org/handle/10986/24919.

World Health Organisation (2020) *Antibiotic resistance*. Available at: https://www.who.int/news-room/fact-sheets/detail/antibiotic-resistance (Accessed: 10 September 2020).

Xiahoa, H. (2019) 'Biostimulant regulations in Europe and the US'. Available at: http://news.agropages.com/News/NewsDetail---32621.htm.

Appendix

Appendix 1: Main commercialized species of seaweed for carrageenan production

	Species	***Main commercial source***	***Type of production***	***Type of carrageenan***
	Chondrus Crispus Irish moss	North Atlantic sea	Wild harvested	κ , λ
	Eucheuma cottonii *Kappaphycus alvarezii*	Philippines, Indonesia, Tanzania, Vietnam Pacific Island	Mostly farmed	κ
EUCHEUMA	*Kappaphycus striatus* *Eucheuma striatum*	Tanzania, Madagascar	Mostly farmed	κ , ι
	Eucheuma denticulatum *Eucheuma spinosum*	Philippines, Indonesia, Africa, Pacific Island	Mostly farmed	ι
	Betaphycus gelatinum *Eucheuma gelatinae*	Hainan Island, China, Taiwan Province of China, Philippines	Wild harvested (manual) and farmed	κ
	Gigartina skottsbergii	Central Chile, Argentina	Wild harvested in lower sublittoral zone (diving)	Mostly λ, few κ , ι
GIGARTINA	*Gigartina canaliculata*	Mexico (Baja California)	Wild harvested (manual)	
	Gigartina Stellata *Mastocarpus stellatus*	France	Wild harvested (manual)	
	Mazzaella laminaroides *Iridaea laminaroides*	Central Chile	Harvested from eulittoral zone (rocks)	κ , ι , λ
IRIDAEA	*Sarcothalia crispata* *Iridaea ciliata*	Central Chile	Harvested from sublittoral zone (diving)	κ , ι , λ
	Hypnea musciformis	Brazil	Harvested from eulittoral zone (rocks)	κ

Source : Adapted form McHugh, 2003 & Alba and Kontogiorgos, 2019

Appendix 2: Main commercialized species of seaweed for agar production

	Species	***Main commercial source***
GELIDIUM	*Gelidium acerosa*	Japan, India, China
	Gelidium amansii	Japan, China
	Gelidium cartilagineum	U.S.A, Mexico, South Africa
	Gelidium corneum	South Africa, Portugal, Spain, Morocca
	Gelidium liatulum	Japan
	Gelidium lingulatam	Chile
	Gelidium pacificum	Japan
	Gelidium pristoides	South Africa
	Gelidium sesquipedale	Portugal, Morocco
	Gracilaria spp.	Philippindes, Indonesia, Chile, India, U.S.A., Argentina, Brazil, China,
	Pterocladia capilacea	Portugal, Egypt, Japan, New Zealand
	Pterocladia lucida	New Zealand
	Ahnfeltia plicata	Russia

Source: Adapted from FAO, 1990; McHugh, 2003

Appendix 3: Main commercialized species of seaweed for alginate production

	Species	***Main commercial source***	***Type of production***
	Ascophyllum	Ireland, UK, Norway, Iceland, France	Wild harvested in eulittoral zone (mechanically)
	Durvillaea	King Island (between Tasmania and Australia)	From storm-cast (illegal to harvest from rocks)
	Ecklonia	South Africa	Collected from beach
LAMINARIA	*Laminaria digitata*	France, Norway, Iceland	Wild harvested in upper sublittoral zone (mechanically)
	Laminaria saccharina	France, Norway	Wild harvested in upper sublittoral zone (mechanically)
	Laminaria japonica	China	Farmed (for food not for alginate)
	Laminaria hyperborea	Ireland, UK, Norway	Wild harvested in mid-sublittoral zone (mechanically)
LESSONIA	*Lessonia nigrescens*	Chile	Harvested from lower eulittoral zone
	Lessonia trabeculata	Chile	Harvested from sublittoral zone.
	Macrocyctis pyrifera Giant kelp	California, Mexico (Baja California), Chile	Harvested rocky bottoms (20m in length)
	Sargassum spp.	Indonesia, Philippines	Wild harvested in eulittoral and upper sublittoral zone (mechanically)

Source: Adapted from McHugh, 2003

Appendix 4: Seaweed pigments and their respective colors

	PIGMENTS	**COLOR**	**SEAWEED**
Chlorophylls	Chlorophyll A	Blue / Green	Green / Brown / Red
	Chlorophyll B	Green Olive	Green
	Chlorophyll C1	Light Green	Brown
	Chlorophyll C2	Light Green	Brown
Carotenoides	α-carothene	Yellow	Red
	β-carothene	Yellow / Orange	Green / Brown / Red
	Antheraxanthin	Yellow	Green / Red
	Fucoxanthin	Orange	Brown
	Lutein	Yellow	Green / Red
	Violaxanthine	Yellow	Green / Brown
	Zeaxanthin	Yellow / Orange	Green / Red
Phycobililiproteins	Allophycocyanin	Blue	Red
	Phycocyanin	Blue	Red
	Phycoerytrhine	Pink	Red

Source: Based on Dumay and Morançais, 2016 & Fleurence and Levine, 2016

Appendix 5: Amino acid profile of red, green, and brown seaweed

		RED	GREEN	BROWN
ESSENTIAL	**Histidine**			Poor
	Isoleucine			
	Leucine	Rich	Rich	Rich
	Lysine	Rich	Rich	Rich
	Methionine	Rich		Poor
	Phenylalanine	Medium	Medium	Medium
	Threonine	Rich		Rich
	Tryptophan			Poor
	Valine	Rich	Rich	Rich
NON ESSENTIAL	**Alanine**	Rich		Rich
	Asparagine			
	Aspartic acid	Rich		
	Glutamic acid	Rich		
CONDITIONAL	**Arginine**	Rich		
	Cysteine	Rich	Poor	Poor
	Glutamine			
	Tyrosine			Poor
	Glycine			Rich
	Ornithine			
	Proline			
	Serine			

Source: Based on Boulho, 2017

Appendix 6: A comparison of the properties of the different carrageenans

Carrageenan type	***Lambda***	***Iota***	***Kappa***
Solubility			
Hot (80 °C) water	Soluble	Soluble	Soluble
Cold (20 °C) water	All salts soluble	Sodium salt soluble	Sodium salt soluble
Hot (80 °C) milk	Soluble	Soluble	Soluble
Cold (20 °C) milk	Thickens	Insoluble	Insoluble
Cold milk (TSPP added)	Increased thickening or gelling	Thickens or gels	Thickens or gels
50% sugar solutions	Soluble hot	Insoluble	Soluble hot
10% salt solutions	Soluble hot	Soluble hot	Insoluble
Gelation			
Effect of cations	Non-gelling	Strongest gels with calcium	Strongest gels with potassium
Gel texture	Non-gelling	Soft, elastic	Firm, brittle
Syneresis	Non-gelling	No	Yes
Hysteresis	Non-gelling	5±10 °C	10±20 °C
Freeze-thaw stability	Yes	Yes	No
Synergy with locust bean gum	No	No	Yes
Synergy with konjac glucomannan	No	No	Yes
Synergy with starch	No	Yes	No
Shear reversibility	Yes	Yes	No
Acid stability	Hydrolysis	Hydrolysis in solution, accelerated by heat; gels are stable	
Protein reactivity	Strong protein interaction in acid		Specific reaction with kappa-casein

Source: from (Imeson, 2009)

Appendix 7: Agar applications in several cultural world region

Applications	Régions		
	Asia	***US/Europe***	***Latin America***
Ice cream	+	+	+
Milk shake	+	+	+
Sherbet	+	+	+
Custard pudding	+	+	+
Cakes	+	+	+
Pie filling	-	+	+
Flat icing	+	+	+
Meringues	-	+	-
Cookies	+	+	+
Candy (agar jelly)	+	+	+
Fruit jelly dessert	++	+	+
Jams, Jellies	+	+	+
Processed cheese	-	+	?
Ferm. Dairy products	+	++	+
Wine clarification	?	+	+
Gelled meats	++	++	?
Dulce de batata	-	-	++
Mitsumame	++	-	-
Red vean jelly	++	-	-
Ager jelly beverages	++	+	+?

Source: from (Armisén and Gaiatas, 2009)

Appendix 8: Application of alginates in food products

Property	Product	Function
Water holding	Frozen Foods (incl. ice cream)	Ensures large ice crystals do not form whilst freezing and that melting is uniform
	Pastry fillings	Gives a uniform, smooth texture
	Syrups	Controls consistency
	Readymade / Bakery icing	Regulates consistency, preventing cracking
	Meringues	Stabilizes structure
	Relish	Relish Allows uniform filling by stabilising the brine
	Dry food mixes	Dry food mixes Hydrophilic algin quickly takes up water for reconstitution
Gelling	Livestock feed meals and Pet Foods	Used as a binder or viscosifier to hold meals / liquid feeds together (low grade alginates used for this)
	Dessert Gels	Dessert Gels Allows fast setting, clear gels to be made with hot or cold water
	Instant Puddings	Instant Puddings Firms puddings
	Pimento olives	Pimento olives Gels together (reconstituted) pimento strips
Emulsifying	Salad dressings	Emulsifies oils
	Flavored sauces for meats	Emulsifies oils and suspends solids within the liquid, giving even consistency
Syneresis*	Processed cheeses	Prevents 'weeping'
	Ice cream	//
	Fruit pie fillings	//
Stabilizing & thickening	Milkshakes	Gives even, creamy consistency
	Beer	Controls head, maintaining structure under adverse conditions
	Fruit juices	Acts to concentrate the drinks flavour and maintains uniformity of pulp suspension
	Whipped toppings	Stabilizes fat dispersion and maintains consistency
	Lemon curd & Fruit pie / Tart fillings	Stabilizes consistency and aids in gelling

*(control of liquid release from gels)

Source: from Kenicer, Bridgewater & Milliken, 2000

Appendix 9: Food and health applications of seaweed pigments

Category	Application	Pigment type
Food	Colorant in food and beverages	β-carotene
	Antioxidant food additives	Fucoxanthin
Nutraceuticals and functional foods	Antioxidant potential in vivo	Zeaxanthin, β-Carotene, Lutein
	Antidiabetic and anti-obesity properties, via suppression of insulin levels, accumulation of adipose tissue, and controlling of hyperglycemia	Fucoxanthin
	Blood-pressure lowering properties and lowers stroke risk factors	Fucoxanthin
	Anticancer activities via antineoplastic effects and ability to inhibit the growth of cancer cells and induce timely and dose depended apoptosis in human breast cancer cells	Fucoxanthin
	Antioxidant, immune modulatory, antiangiogenic, antimalarial activities, and anti-inflammatory effects	Astaxanthin, Fucoxanthin
Pet food	Improve appearance of pet foods while imparting biological effects such as antioxidant, and immune enhancing properties	Astaxanthin
Animal feed	To enhance the colour of animal food products such as poultry (eggs, meat colour), seafood (fish (salmon, trout), and crustaceans, shrimps, krill).	Astaxanthin

Source: from Aryee, Agyei & Akanbi, 2018

Appendix 10: The major groups of antioxidant compounds in macroalgae with specific examples

General category	Example compounds
Carotenoids	β-carotene
	Fucoxanthin
	Antheraxanthin,
	lutein,
	violaxanthin
	xanthophylls
	zeaxanthin
Phoenolic compounds	Stypodiol
	Isoepitaondiol
	Taondiol
	Terpenoids
Phycobilin pigments	Phycoerythrin
	Phycocyanin
Polyphenols	Catechin
	Epicatechin
	Gallate
	Flavonoids
	Phlorotannins
Sulphated polysaccharides	Fucoidan
	Alginic acid
	Laminaran
	Sulphated galactans (λ carrageenan)
	Porphyran
Vitamins	Ascobate
	Vitamin A

Source: Adapted from Cornish and Garbary, 2010

Appendix 11: *Ascophyllum nodosum* Nutritional Factsheets

Compound	Unit	Average content per 100 of dehydrated seaweed
Energy	Kcal	211
Water	g	10.8
Minerals	g	18.9
Protein	g	7.2
Carbohydrates	g	18.5
Dietary fibers	g	41.8
Lipids	g	2.8
Saturated Fatty Acids	g	0.11
Monounsaturated Fatty Acids	g	0.19
Polyphenols	g	3.6
Sodium	mg	2.859
Magnesium	mg	836
Phosphorus	mg	162
Potassium	mg	2.269
Calcium	mg	1652
Manganese	mg	2.5
Iron	mg	21.8
Copper	mg	0.7
Zinc	mg	6.4
Iodine	mg	68.2
Selenium	µg	6.7
B-carotene	mg	4
Vitamin D	µg	1
Vitamin E	mg	14
Vitamin K	µg	1.017
Vitamin C	mg	94.8
Vitamin B1	mg	0.3
Vitamin B2	mg	1.0
Vitamin B3	mg	2.7
Vitamin B5	mg	0.02
Vitamin B6	mg	5.6
Vitamin B8	µg	18.4
Vitamin B9	µg	22.7
Vitamin B12	µg	2.1

Source: Translated from CEVA, 2011

Appendix 12: Non-exhaustive table of the benefits of certain seaweed and compounds of interest in animal nutrition and finished product qualities

	SEAWEED	PERCULIARITES	TYPE	PROPERTIES	REFERENCE
Ruminant	*Ascophyllum nodosum*	Rich in minerals	Dairy farm	Correction of diets deficient in minerals for milk production	(Makkar *et al.*, 2016)
			Other	Improvement of oxidative stress induced by transport heat Improved immunity Antioxidant Improved digestibility of poor-quality forage, increased fiber digestibility Reduction of pathogenic microorganisms Increased steak color	(Makkar *et al.*, 2016)
	Scenedesmus	/	All	Stimulation of the intestinal flora	(CEVA, 2011)
	General Seaweed	Rich in fattys acids (n-3)	Dairy farm	Increased lactation period Average protein increase in milk Increased milk production Improved immune function Characteristic improvement of the carcass	(Makkar *et al.*, 2016)
	Laminaria Saccharina	13% protein	All	High nutritional value	(Makkar *et al.*, 2016)
	P. palmata	Up to 20% protein	All	High nutritional value Appetizing	(Makkar *et al.*, 2016)
Pigs	*Laminaria*	Rich in iodine	/	Increase concentration iodine in pork	(Makkar *et al.*, 2016)
	Ascophyllum	Rich in iodine	/	Increase concentration iodine in pork	(Makkar *et al.*, 2016)

Appendix 12 (continued)

	SEAWEED	PERCULIARITES	TYPE	PROPERTIES	REFERENCE
Poultry	*Enteromorpha prolifera*	/	Meat hen	Food intake Average daily gain while reducing abdominal and subcutaneous fat thickness Thus improving the quality of the breast meat	(Makkar *et al.*, 2016)
	General Seaweed	/	Hen	Improve immune status Decreases the microbial load in the digestive tract Increased quality of poultry meat and eggs.	(Makkar *et al.*, 2016)
	/	Rich in protein	Hen	Improve egg production and quality (weight, shell thickness and yolk color) Better animal health	(Makkar *et al.*, 2016)
	/	Rich in pigment	Hen	Increased yellow color of egg yolk Best color of chair color	(Vinoj Kumar and Kaladharan, 2007)
	Calcified red seaweed	Rich in calcium	Meat hen	Better bone health	(Makkar *et al.*, 2016)
Aquaculture	*Ulva spp*	/	/	Increased growth performance Stress resistance Quality of the finished product increased	(Linden, 2014)
	Pedina	Rich in calcium	Pearl or nectariferous molluscs	Speed up the pearl formation process	(CEVA, 2011)
		Bromophenol	All	Improve the organoleptic quality of the product	(CEVA, 2011)
General breeding	*Padina* *Sargassum* *Turbinaria* *Dictyopteris undulata*	Rich in vitamin	/	Antioxidant Stimulation of the immune system Stimulation of reproductive functions	(CEVA, 2011)
	/	PUFAs	/	Decreased cardiovascular risks	(CEVA, 2011)